Electrical Engineering Papers

By Benjamin G. Lamme

This volume contains a collection of the author's more important engineering papers presented before various technical societies and published in engineering journals and elsewhere from time to time

1919

Published by

Westinghouse Electric & Mfg. Co.

East Pittsburgh, Pa.

Permission to reprint these papers has been granted by the owners of the copyrights and individual credit is given in the foreword of each paper

PREFACE

The papers of Benjamin G. Lamme have always interested American engineers Distributed in many publications, some quite inacessible to readers, it is indeed a fortunate circumstance which now makes available a collection of these papers for engineers, professors, instructors, and students and all those interested in, and able to understand, the progress of electrical engineering.

Besides his achievements in the art of engineering, Mr. Lamme has been gifted with the faculty for clear expression and explanation, which is one of the rarest to be found in the engineering profession The collection begins with his early paper on the Polyphase Induction Motor, which, in its time, was a primer of the characteristics and operation of such motors in the hands of the numerous users of these machines. Then follows a period in which he prepared few papers, but which was one of great personal activity Then comes his epoch-making paper, in 1902, before the American Institute of Electrical Engineers in New York on the Single-Phase System of the Washington Baltimore and Annapolis Railway. Up to this time, the development of the electric railway systems, as a whole, was at a point of complete stagnation, in the utilization of 600 volts direct current, and this paper represented the first great and successful attempt to break away from established practice toward materially higher trolley voltages. Its advent gave an impulse to the entire subject of the electrification of railroads greater than any other it had ever received, leading to the complete abandonment of old and apparently well established standards, as well as to later attempts to meet the new conditions with higher direct-current voltages.

In 1904, there are two papers, one on a 10,000 Cycle Alternator, and another on the Synchronous Motor for Regulation of Power Factor. In the same year, he contributed a discussion to the subject of Single-Phase Motors which ranks as one of the clearest and most suggestive descriptions of this type of motor, which owes to him its development and use.

Recognizing the importance of closer relations with the American Institute of Electrical Engineers, we find him contributing, from time to time, papers on Commutation, on the Homopolar Dynamo, on Rotary Converters, on Turbo Generators, on Losses in Electrical Machinery, and on Engineering Education, etc. It is safe to say that these papers will be read in their present form by many who enjoyed them when they came out originally, and their contents will perhaps be more appreciated today than at the time when they were written.

To all those who have followed the development of electrical engineering in America during the past thirty years, and to all those who would like to know the historical development of electrical apparatus, the series of papers which appeared in the Electric Journal, on the History of the Railway Motor, of the Direct-Current Generator and of the Alternating-Current Generator.

and the History of the Frequencies, now collected for the first time, will form most interesting reading Here Mr. Lamme had an opportunity to recount the work of himself and of his associates, adding to it the clarity and lucidity which have always marked his style.

I think those who have known Mr. Lamme's interest in education and in his instruction of young engineers will be glad to find reprinted in this volume two of his contributions on the subject of engineering education. The wholesome, sound sense which permeates these papers cannot fail to appeal to all, and to impress the reader with the sound judgment of their author.

Although these papers represent a work of thirty years, during which time Mr. Lamme has been continuously associated with the great company which bears the name of Mr. Westinghouse, yet I believe they do not complete his whole life work Those of us who have had the good fortune to have known him for a score of years, or more, well know that many contributions will yet be made by him to the art and science of electrical engineering The publication by the Westinghouse Company of this collection of Mr. Lamme's engineering papers on the anniversary of his first connection with this company, thirty years ago, represents a most dignified appreciation of his services to the entire engineering profession.

B. A. Behrend

Boston Mass.
April 2, 1919.

CONTENTS

THE POLYPHASE MOTOR

FOREWORD—This paper was prepared in the early part of 1897, or over twenty-two years ago. It was presented at the twentieth convention of the National Electric Light Association at Niagara Falls on June 10, 1897, and was prepared for the purpose of illustrating the characteristics and properties of the Westinghouse Type C motor which, at that time, was beginning to attract much attention. This motor was radically new in that it had a "cage" type secondary winding for large, as well as small, sizes, whereas, it was generally believed that the cage type was only suitable for small power machines, due to lack of starting torque.—(ED.)

INTRODUCTION

THE polyphase motor is usually treated from the theoretical standpoint, and the results obtained are of interest mainly to designers and investigators. Such treatment has been principally of a mathematical nature, the object being to show how the various characteristics of the motor may be predetermined. In the following treatment of the subject, the general operation of the motor will be explained in a non-mathematical way by the use of diagrams which illustrate its characteristics under different conditions. Only the non-synchronous type of motors will be considered, and no distinction will be made between two-and three-phase motors; for, if properly designed, they are practically alike in operation.

It is necessary to understand the characteristics of the polyphase motor in order to consider properly its application to the different classes of work to be met with in practice. These characteristics can be presented in the most intelligible manner by means of curves, which represent the relations between the speed, torque or turning effort, horse power expended and developed, amperes, etc. The speed-torque curve, which represents the speed in terms of the torque, is the most important one, as upon this depends the adaptability of the motor to the various kinds of work. The starting conditions also depend upon the speed-torque characteristics. The other curves that are of importance in practice are the current, efficiency and power factor. As these are dependent, to some extent, upon the speed-torque curve, this will be considered first. Before treating of its characteristics a short description of the motor itself will be given.

CONSTRUCTION AND WINDING

The polyphase motor, like a direct-current motor, consists primarily of two parts, one stationary and the other rotating, each of which carries windings. The inside bore, or face, of the *stationery* part is generally slotted, and carries windings that resemble those of the *rotating* part, or armature of an ordinary direct-current motor without commutator. The rotating part is also slotted on its outside face, and there are windings in the slots. Both cores, or bodies, are built up of thin iron or steel plates. The general arrangement is shown in Fig. 1. One of these windings, generally

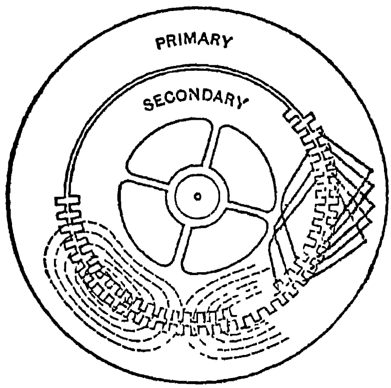


FIG. 1—ARRANGEMENT OF WINDINGS OF THE POLYPHASE MOTOR AND THE MAGNETIC FIELDS WHICH ARE PRODUCED.

that on the stationary part, receives current from a two or three-phase supply circuit. The coils of this winding, although distributed symmetrically over the entire face of the core, are really connected to form distinct groups which overlap each other. These windings form the two or three circuits in the motor. When alternating electro-motive forces are applied to these circuits, currents will flow which set up magnetic fields in the motor. These alternating fields in turn generate electro-motive forces in the windings. Part of the current flowing in the windings represents energy expended usefully, or in heating, and part serves merely as magnetizing current. The latter, like the magnetizing current of a direct-current machine, is dependent upon the dimensions of the magnetic circuit and upon the magnetic density in the various parts. Even when the motor is running with no load the magnetizing current is required.

The second part of the motor, generally the rotating part, receives no current from the supply circuit. The magnetic fields set up by the first set of windings pass through the second windings, and, under certain conditions, generate electro-motive forces in them. If the second windings are arranged to form closed circuits, currents will flow in them. These currents are entirely separate from those of the supply circuits.

Speed and Slip

When running, the motor has a maximum speed that is approximately equal to the alternations of the supply circuit divided by the number of motor poles in each circuit. This is the no-load speed. As the motor is loaded, the speed falls off almost in proportion to the load. The drop in speed is sometimes called the

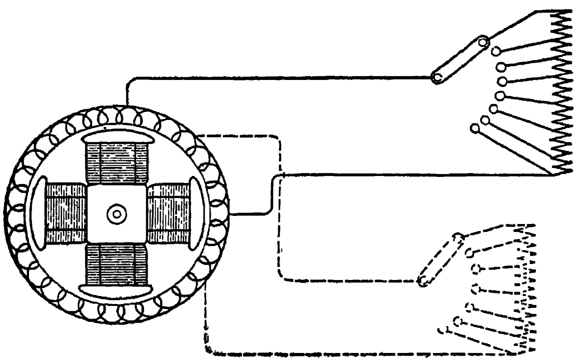


FIG.2—DIAGRAM OF TWO-PHASE ALTERNATING-CURRENT GENERATOR, ROTATING-FIELD TYPE.

"slip." This is usually expressed in percent of the maximum speed. If, for instance, a motor has a maximum speed of 1000 revolutions and drops fifty revolutions below this at full load, it has then a slip of five percent.

Torque and Armature Current

With this type of motor, a drop in speed is necessary for developing torque. A fairly simple illustration of this action may be obtained by considering the operating of an alternating current generator under certain conditions. We will take a type of alternator having a stationary armature and a rotatable field magnet, which can be driven at various speeds. Leads are carried out from the armature to adjustable resistances. To avoid complexity, the armature circuits and the resistances are considered as non-inductive. The field coils are excited by direct current. Fig. 2 shows this arrangement.

When the field is rotated at a certain speed, with the field coils charged, there is an alternating electro-motive force set up in the armature winding. When the armature circuit is closed through a resistance a current will flow and the armature will develop power. The power developed by the armature is slightly less than the power expended on the field shaft, which is proportional to the product of the speed and the turning or driving effort—*i. e*, torque on the shaft. Consequently, at a given speed, a driving effort is required at the field shaft, corresponding to the power developed by the armature. If the armature current is increased or decreased, the power developed is increased or decreased also, and the driving effort will vary in proportion.

Let the field now be rotated at one-half the above speed. The armature electro-motive force becomes what it was before. Reducing the resistance in the armature circuit also to one-half, the same current as before will flow. The power developed by the armature is now one-half and the speed of the field is one-half, consequently, the driving effort or torque is the same as before. Reducing the speed further, and decreasing the resistance in the armature circuit in proportion, to keep the armature current constant, we find the driving effort on the field remains constant. Finally, if we reduce the speed so much that the external armature resistance is all cut out, and the armature is short circuited on itself with the same current as before, the same driving effort is still required.

The field is now rotating very slowly, and the alternations in the armature are very low, being just sufficient to generate the electro-motive force required to drive the armature current against the resistance of the windings. Any further reduction in speed will diminish the armature electro-motive force, and hence the armature current must fall, the power developed be diminished and the driving effort also fall in proportion. An increase in speed will increase the armature current, and thus increase the driving effort required.

If but one armature circuit is closed, the power developed will pulsate as the armature current varies, from zero to a maximum value, and the driving effort will also vary. But if the armature has two or more circuits having different phase relations, it may develop power continuously and the driving effort will then be continuous.

Illustration of "Slip"

The armature has been considered as stationary and developing power while a certain driving effort was applied to the field. According to the well known law that any force is met by an opposing force, the armature must have a certain resisting effort. The armature really tends to rotate with the field, and the resisting effort is exerted to prevent this.

Assume the armature to be arranged for rotation, but locked, in the above operations. Release the armature, attach a brake, and adjust for a torque equal to the resisting effort of the armature. The armature just remains stationary. Speed up the field, and the armature will speed up also, keeping a certain number of revolutions behind the field. This difference in speed is that required for generating the electro-motive force necessary for sending the current through the armature. The alternations in the armature will remain constant for a given armature current, independent of the speed at which the armature is running.

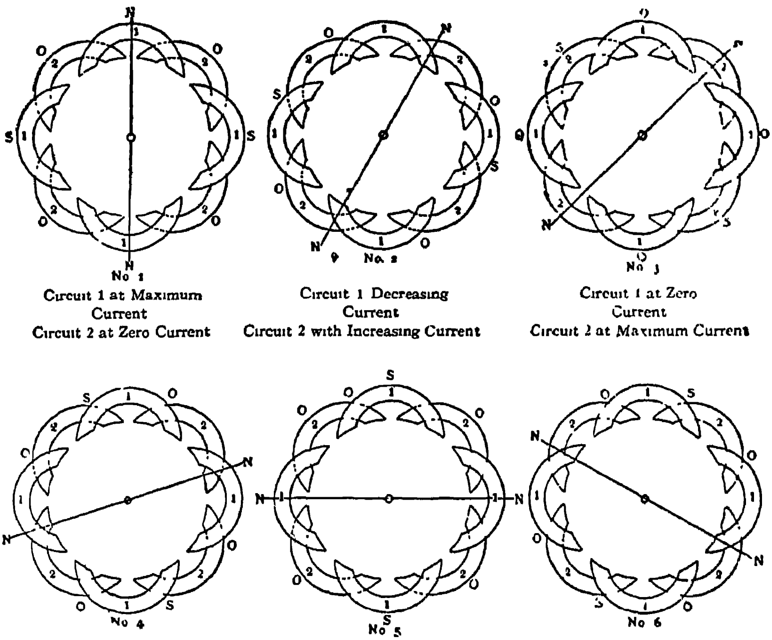
If the brake be tightened, the armature must drive more current through its windings to develop the required effort, the armature alternations must hence increase, and the armature will therefore lag behind its field more than before, or the "slip" is increased. If the brake be loosened, the armature will run nearer the speed of the field. If the field be driven at a constant speed and the brake be released, the armature will run at practically the same speed as the field.

If the winding consist of but one closed circuit, the torque developed by the armature varies periodically, and that developed by the brake will vary also, but to a less extent, as it is steadied by the inertia of the rotating armature. But with two or more circuits having different phase relations, arranged for constant power developed in the armature windings, the torque developed is also constant at all times. Consequently, for constant torque at the brake, there should be two or more phases in the armature windings.

Difference Between Illustration and Actual Case

This explanation of the development of torque in the short-circuited armature is merely an attempt to illustrate certain of the actions in the polyphase motor armature by a comparison with the operations of other apparatus, that is, in general, much better understood. We cannot infer, from the above illustration, that an alternating-current generator would run as a motor under the

assumed conditions, for, in the above operations, mechanical power is supplied to the field shaft, and mechanical power is delivered by the rotating armature to the brake. There is no true electro-motor action; that is, there is no transformation of electrical power supplied to mechanical power developed.



Circuit 1 at Maximum Current
Circuit 2 at Zero Current

Circuit 1 Decreasing Current
Circuit 2 with Increasing Current

Circuit 1 at Zero Current
Circuit 2 at Maximum Current

Circuit 1 Increasing in Reverse Direction
Circuit 2 Decreasing

Circuit 1 at Maximum in Reverse Direction
Circuit 2 at Zero

Circuit 1 Decreasing
Circuit 2 Increasing in Reverse Direction

FIG 3—DIAGRAM SHOWING PRODUCTION OF ROTATING MAGNETIC FIELD BY TWO-PHASE CURRENTS

The action of the short-circuited armature of the above generator and that of the polyphase motor are very similar in regard to drop in speed for developing torque But in the polyphase motor, instead of the mechanically rotated field magnet, there is a stationary core provided with two or more windings which carry currents having different phase relation. These windings are placed progressively around the core, either overlapping or on separate poles. When the currents flow in the windings, resultant magnetic poles or fields are formed, which are progressively shifting around the axis of the motor. The closed or short-circuited armature, rotating in this field, develops torque by dropping in

speed, in the same way that it developed torque with mechanically rotated field magnets. But electrical power, instead of mechanical, is now supplied to produce the shifting of rotating field, and the conversion from electrical power supplied to the field windings, to mechanical power developed by the armature shaft is a transformer action which does not appear in the above illustration.

Rotating Magnetic Field Electrically Produced

Fig. 3 shows diagrammatically a progressively shifting field, with two overlapping windings arranged for two-phase currents. Coils 1-1, etc., form one circuit, while coils 2-2, etc., form the other. Starting with the instant when the current in 1 is at its maximum value, the magnetizing force of this set of coils must be at its maximum. The current and magnetizing force of circuit 2 are at zero value. Four poles or magnetic fields, alternating N-S-N-S around the core, are formed directly over coils 1. As the current in one begins to decrease, that in 2 rises. We then have the combined magnetizing forces of the two overlapping windings. These two magnetizing forces act together at some points and oppose at others. The resultant magnetic field shifts to one side of the former position. As the current in 1 gradually falls to zero and 2 rises to its maximum value the magnetic field shifts around until it is directly over coils 2. If the current in 1 should next increase in the same direction as before, while 2 diminished, the magnetic poles would shift back again to their former position. But the current in 1, after reaching zero value, rises in the opposite direction, while that in 2 falls. This shifts the resultant poles forward instead of backward, and they gradually shift ahead until they are again directly over coils 1. But the "N" poles have shifted around until they now occupy the former position of the "S" poles. Thus, with the current in 1 passing from a maximum in one direction to a maximum in the opposite, the poles have shifted forward the width of one polar space. Current in 2 next rises in a reversed direction and the poles shift forward until, when the current in 2 is a maximum, they are over coils 2.

In the diagrams, Nos. 1, 2, 3, etc , show the positions of the shifting field under certain conditions of current in the two circuits. In No. 2, the position shown is an arbitrary one, for it depends upon the relative values of the currents in the two circuits. With the two currents equal, the position of the line N-N would be half-way between coils 1 and 2.

These diagrams show that the magnetic field due to two-phase currents in properly arranged windings shifts progressively around the axis, just as if the field were rotated mechanically.

Speed-Torque Curve

In polyphase motors, the part that resembles the field in the above description and which receives the current from the line, is usually called the primary, on account of its electrical resemblance to the primary of a transformer. The equivalent of the armature in the preceding description is called the secondary. If the alternations of the supply circuit are constant, the reversals of the currents in the field or primary will occur at a uniform rate and the magnetic field will shift around its center at a definite speed, depending upon the rate of alternation of the supply circuit and the number of poles in each circuit of the motor. If the armature or secondary rotates at the same speed as the field shifts, there will be no reversals or alternations in its magnetism, and there will be no currents and consequently, no torque. If a load is thrown on, the speed will drop and the resultant alternations in the secondary will generate electro-motive forces which will drive currents through the windings, and thus develop torque. The speed will continue to fall, and the secondary electro-motive forces will continue to increase until a torque sufficient for the load is developed.

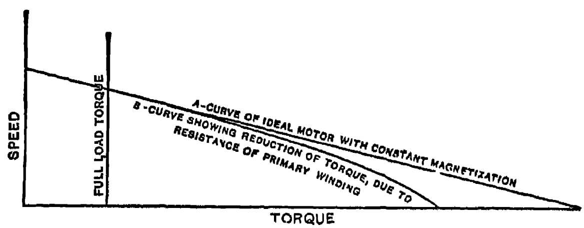


FIG. 4—SPEED TORQUE OF POLYPHASE MOTOR

Increasing the load on the motor, the speed should fall and the torque increase until zero speed is reached. The speed-torque curve would then be of the form shown in Fig. 4, curve "A." But the shape of this curve is modified to a great extent in actual motors by certain effects which cannot be entirely eliminated.

Primary Resistance Reduces Magnetization at Heavy Loads

In the case of the revolving field, the magnetization was supposed to remain constant under different conditions. But in the motor primary, the magnetism of the primary is not constant under all conditions and it does not all pass through the secondary

circuits. The primary windings necessarily have some resistance, and a certain electro-motive force is required to drive the primary current through the windings. With a constant applied electro-motive force, the primary counter-electro-motive force will diminish as the drop in primary resistance increases, and the magnetic field required will diminish also. Consequently, to develop the required secondary electro-motive force for driving the secondary current through the windings the speed must drop more than shown by curve "A" in Fig 4. This gives a speed-torque curve as shown by curve "B," in Fig. 4. Instead of being a straight line it is somewhat curved.

Magnetic Leakage Limits Maximum Torque

But there is a still more important effect in the motor. The primary and secondary currents, and their consequent magnetizing forces, are opposed to each other. The result is that part of the primary magnetism threads across between the primary and secondary windings without passing into the secondary. Thus, the electro-motive force of the secondary is reduced, or, for a required secondary electro-motive force, the secondary alternations must be increased. This means a further drop in speed.

The secondary currents also tend to form local magnetic fields around their own coils. These local fields are alternating and set up electro-motive forces in the secondary circuits. In consequence, the electro-motive forces generated by the magnetism from the primary have to drive currents, not only against the resistance of the secondary windings, but also against these local electro-motive forces. This necessitates a further drop in speed for the required torque. These local electro-motive forces depend upon the secondary alternations and, therefore, vary with the drop in speed, and are greatest at zero speed. This introduces a very complicated condition in the secondary circuits. These magnetic fields which thread around only the primary or secondary windings are called the magnetic leakages, or stray fields, or the magnetic dispersion.

If the magnetic leakage is relatively large, that is, twenty to twenty-five percent of the total induction, and the secondary resistance is low, the speed-torque curve will have the peculiar shape shown in Fig. 5. This curve shows the torque increasing as the speed falls, until a certain maximum is reached. Beyond this point the torque diminishes with further drop in speed. If the motor is loaded to the maximum torque, a slight increase in load causes a further drop in speed, the torque diminishes and the motor

stops. As a consequence, the normal rating of the motor must be considerably below this "pulling-out point." The margin necessary depends upon the nature of the load to be carried.

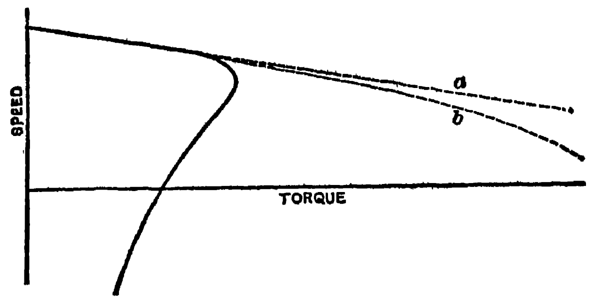


FIG. 5—SPEED TORQUE OF POLYPHASE MOTOR, SHOWING EFFECT OF MAGNETIC LEAKAGE

The starting torque, speed regulation, etc., of the polyphase motor depend upon the form of the speed-torque curves. The different methods of varying the form of these curves will be considered next.

Effect of Secondary Resistance on Speed Curve

As the secondary electro-motive force is that necessary to drive the secondary currents through the windings, it follows that the electro-motive force required must depend upon the resistance of these windings. A larger resistance means a larger electro-motive force for the required current, and, therefore, a greater number of secondary alternations, or a greater drop in speed. The torque being held constant, any variation of the secondary resistance requires a proportionate variation in the slip. If the slip with a given torque is 10 percent, for instance, it will be 20 percent with double the secondary resistance, or 50 percent with five times the resistance. This is true only with the primary conditions of constant applied electro-motive force and constant alternations. The secondary resistance may be in the windings themselves, or may be external to the windings but part of the secondary body, or it may be entirely separate from the machine and connected to the windings by the proper leads.

Fig. 6 shows the speed-torque curves for a motor with different resistances in the secondary circuit. In curve "A" the secondary resistance is small. In curve "B" the secondary resistance is doubled. The maximum torque remains the same but the slip for any given torque is doubled. This motor starts much better

than that in curve "A." In curve "C," the resistance is again doubled and the slip is also doubled. The starting torque is increased but the slip is rather large at the rated torque, "T." In curve "D," the slip is again doubled. In this case the torque is high at start and falls rapidly as the speed increases. In curve "E," the maximum torque is not yet reached at zero speed. Continuing these curves below the zero-speed line, that is, running the motor in the reverse direction, we get the general form of these different speed-torque curves. They are all of the same general shape, and all have the same maximum torque.

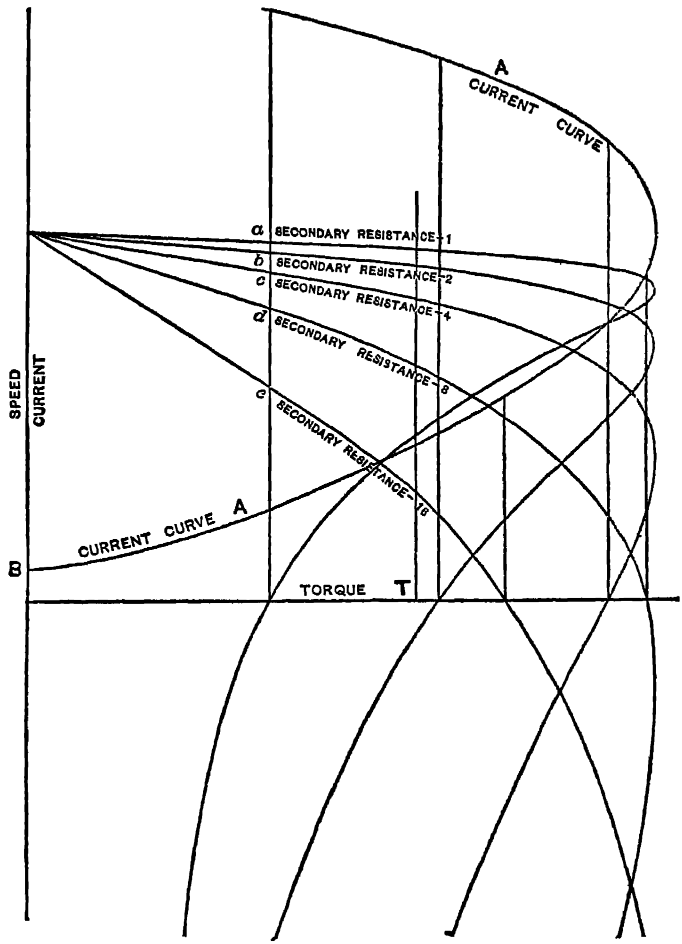


FIG. 6—SPEED-TORQUE AND CURRENT-TORQUE CURVES OF POLYPHASE MOTOR WITH SECONDARIES OF DIFFERENT RESISTANCE

So far as torque is concerned, curve "D" is the best for starting. But for running, curve "A" gives the least drop in speed. Consequently, if a resistance is introduced at start that will give the speed-torque curve "D," it should be cut out or short-circuited for the running condition. This is one method of operation that has been much used.

Current Curve

In determining the best starting condition, the current supplied to the primary must be considered in connection with the speed-torque curves. This current is plotted with the series of speed-torque curves shown in Fig. 6. Referring to this figure, curve "A" represents the primary amperes in terms of torque. Starting at the point "B," of no-load, or zero torque, it rises at a nearly uniform rate until maximum torque is approached; that is, below the point of maximum torque the current is nearly proportional to the torque, but beyond this point the current continues to increase and reaches a maximum at the torque represented by zero speed. At reversed speed this current is further increased. This one current curve holds true for all the speed-torque curves, "A," "B," "C," "D," etc.

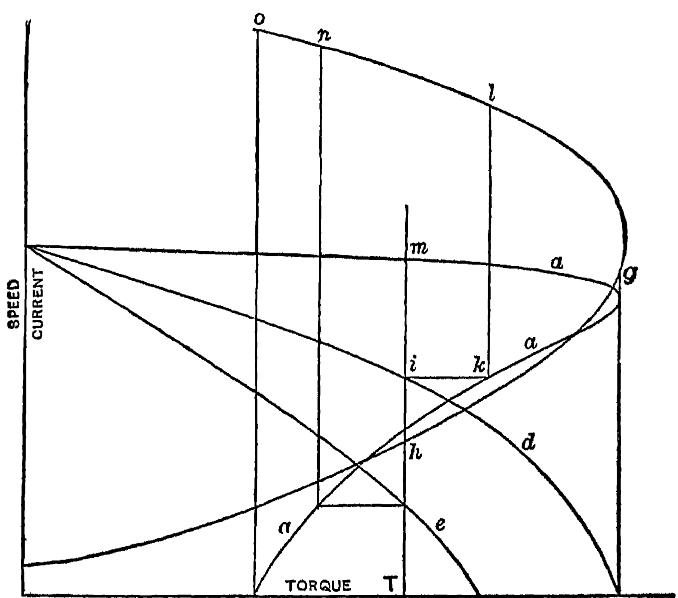


Fig. 7—Starting Conditions with Variable Secondary Resistance

Comparing the different curves, we see that "A" takes the most current at start, and gives low torque; "B" takes less current than "A," and gives more torque; "C" takes less current than "B"; "D" takes less current than "C" and gives the maximum torque at start; "E" takes less current than "D," and develops less torque; but the current and torque are very nearly in proportion over the whole range. From this we see that a speed-torque curve of the form of "D" or "E" is decidedly better for starting than "A" or "B." But for running at less than the maximum torque there is no advantage, so far as current is concerned, in curve "D" over curve "A," and the speed regulation of "D" is poor.

STARTING WITH VARIABLE SECONDARY RESISTANCE

Fig. 7 represents the conditions of speed, current, etc., when a variable secondary resistance is used at start. The motor starts at "F" on curve "D," and takes a current "G." The current falls to "H," while the speed rises to "I," which corresponds to the normal torque "T" at which the motor will run under the given conditions as long as the motor operates on curve "D." The speed will remain at this point. If the resistance in the secondary is now short-circuited, and the load thus shifted to the speed-torque curve "A," the torque at the speed "I," increases to "K" on torque curve "A." The current corresponding to this is "L." As the torque at "K" is greater than the normal torque "T," the motor speed will increase until normal torque is reached again at "M," while the current falls from "L" to "H."

At the moment of cutting out the secondary resistance there was a very considerable increase in the current. By arranging the starting resistance in the secondary so that the motor will start at some curve intermediate between "A" and "D" and thus take more current at start, somewhat less would be required upon switching to curve "A." If curve "E" is used for starting, and if the torque required when speeding up is greater than that at the point where curves "A" and "E" cross each other, the motor will not pull up because in switching from "E" to "A," the torque falls, and the motor will stop. The current on switching over increases to "N," and then rises to "O" as the motor stops. In this case the resistance that gives curve "E" is too great, and a lower starting resistance is required; with a large number of resistance steps small variation of current is secured.

By making several steps of the secondary resistance, so that it may be cut out gradually, the motor may be made to pass

through a series of speed-torque curves with much smaller variations of current than shown in the preceding diagrams. This method has been used to some extent, but requires collector rings or a complicated switching arrangement in connection with the motor secondary.

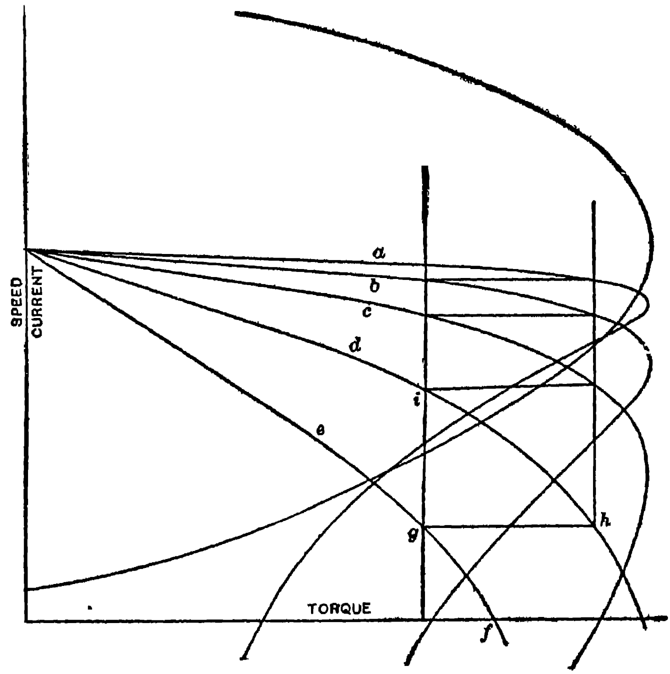


FIG. 8—STARTING CONDITIONS WITH FIVE SECONDARY RESISTANCE STEPS.

Fig. 8 shows the conditions for starting and speeding up with five speed-torque curves. The motor starts on curve "E" at "F." The speed rises to "G." The motor is then switched to curve "D," the torque rising to "H." The speed then rises to "I." In this way the motor passes successively from "D" to "C," "B" and "A," until the full speed is reached. The currents at no time reach very high values.

Plotting the current in terms of speed, the use of a large number of steps is shown to better advantage. This is shown in Figs. 9 and 10. Fig. 9 shows the same starting conditions as Fig. 7 with curves "D" and "A." The current starts at "A" and falls to "B." The resistance is then short-circuited and the current rises to "C" and then falls to "D," which is the same as "B." If

"A" had been higher at start, "C" would have been lowered slightly. But as the time required for passing from "A" to "B" is generally greater than that from "C" to "D," "C" may be higher than "A." If the motor is not required to develop such a

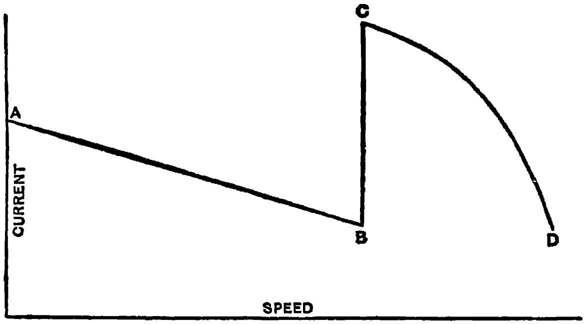


FIG. 9—CURRENT SPEED CURVE FOR MOTOR STARTING, AS IN FIG. 7.

large torque when pulling up, then "C" may be lowered while "A" is left unchanged.

In Fig 10, the currents in terms of speed are shown for five steps with the five speed-torque curves of Fig 8. The starting current "A" is low, and none of the currents, when switching from

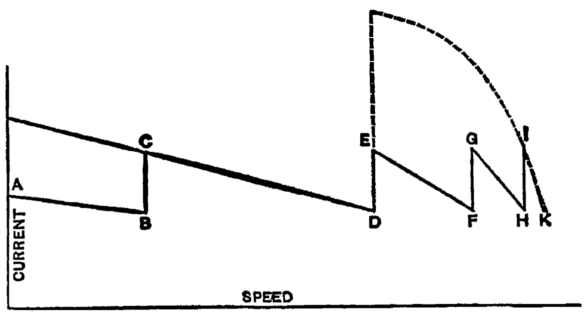


FIG. 10—CURRENT SPEED CURVE FOR MOTOR STARTING, AS IN FIG. 8
DOTTED LINES SHOW SAME CURVE AS FIG 9

one curve to another, is large. The dotted lines show the corresponding currents for two steps, as in Fig. 9.

Motors for Variable Speed Work

For variable speed work, such as cranes, elevators, etc., the series of curves in Fig. 6 shows one method of regulating the speed By varying the secondary resistance over a wide range, any speed from zero to maximum may be obtained with any torque up to

the maximum. This requires the use of collector rings and adjustable rheostats. The variations in speed are obtained by wasting energy in resistance. For a given torque the same power is expended on the motor whether the speed is zero or maximum. To obtain a certain torque at start requires as much power as when running at full speed.

An analysis of the motor shows another way in which the speed-torque curves may be varied. In Fig. 6, all the curves show a certain maximum torque which is the same in all cases; but this is with the condition of constant primary electro-motive force. By varying the electro-motive force applied to the primary we may obtain a quite different series of curves. Taking, for ex-

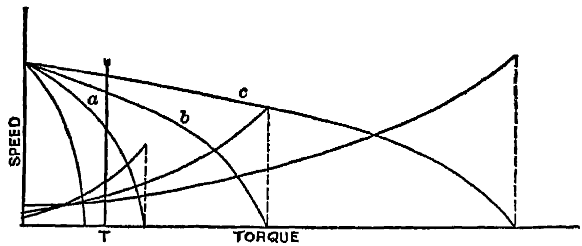


FIG 11—SPEED-TORQUE AND CURRENT-TORQUE CURVES FOR POLYPHASE MOTOR WITH DIFFERENT VOLTAGES APPLIED

ample, a speed-torque curve of the form "A" in Fig. 11, and applying a higher electro-motive force to the primary, a curve is obtained of the same shape as "A," but with a much higher point of maximum torque. Lowering the applied electro-motive force, the maximum torque is lowered. The torques at any given speed are raised or lowered in the same proportion as the maxima are varied. At any given speed the torques are proportional to the square of the electro-motive forces applied. This relation holds good for any form of the torque curve, whether of the shape "A," "D," or "E," shown in Fig. 6.

The current curves are also shown in Fig. 11. They all have the same general shape, but have different maximum values, these being proportional to the electro-motive forces applied. The speed-torque curve "A" in Fig. 11 has the same shape as "D" in Fig. 6, which gave too great a drop in speed. In Fig. 11, curve "B," which is the same form as "A," gives less speed drop for the same torque. Curve "C" gives less than "B," and has fairly good speed regulation from no-load up to normal torque "T." But

this result is obtained at the expense of increased induction in the iron, and large no-load or magnetizing current due to the higher electro-motive force, is required. If it is possible to obtain a speed-torque curve like "C" in Fig 11 with the normal electro-motive force applied, we can obtain good speed regulation from no-load up to the rated torque, and shall be able to start the motor with the maximum torque it can develop. Then, by lowering the applied electro-motive force, the same form of speed-torque curve will be retained, but the starting torque and starting current may be lowered to any extent desired.

VARIABLE SPEED BY VARYING VOLTAGE

Returning to Fig 5, it was stated that the peculiar shape of this curve, with the torque falling rapidly after reaching a maximum value, was due mainly to magnetic leakage between the primary and secondary windings. But if the motor is so proportioned that the leakage is very small compared with the useful field, the speed-torque curve takes a quite different shape. The maximum torque is increased directly as the magnetic leakage is diminished. This is shown in Fig. 12. Here "A" is similar in shape to curve "A" in Fig. 6; "B" represents the speed-torque curve with the magnetic leakage reduced one-half; "C" represents it with about one-half the leakage of "B," and "D" with one-half that of "C."

In comparing Figs 6 and 12, it may be noted that "A" in one is the same form as "A" in the other, although drawn to a different scale. In Fig. 12, "B" has the same shape as in Fig. 6, but has a different maximum value. The same is true of curves "C" and "D" in the two figures. By lowering the applied electro-motive forces for curves "D," "C" and "B" of Fig. 12, so that the maximum torques are equal to that of "A," as shown by the dotted curves, we get practically the same curves as in Fig. 6.

Curve "D," in Fig. 12, gives as good running conditions as curve "A" in Fig. 6, having about the same drop in speed at the normal torque "T." We have, then, in "D" a curve which starts at the point of maximum torque, and which also has a small drop in speed at the normal load. The objection to this curve is that the starting current and starting torque, although in the proper proportion to each other, are both much greater than is necessary or desirable. By reducing the applied electro-motive force at start, however, lower torques and currents are obtainable. In this way we may combine good starting and running conditions in one

motor without the use of starting resistances, and with a secondary that has no resistance except that of its own windings. Fig. 13 shows the speed-torque and current curves of such a motor with the applied electro-motive force varied over a considerable range.

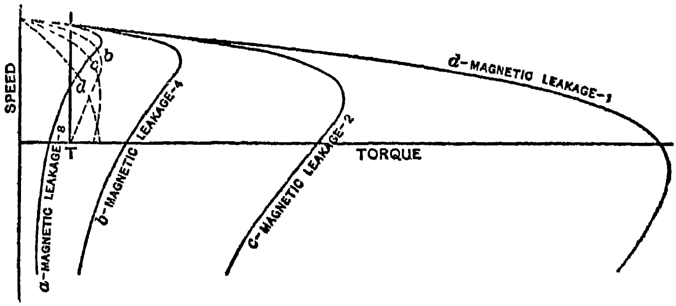


FIG. 12—SPEED-TORQUE CURVES OF POLYPHASE MOTOR SHOWING EFFECT OF MAGNETIC LEAKAGE. DOTTED LINES SHOW CURVES b, c, d WITH REDUCED VOLTAGE

If but one electro-motive force is desired for starting and speeding up, and the motor is then to be transferred to the working electro-motive force, the speed-torque curves should preferably

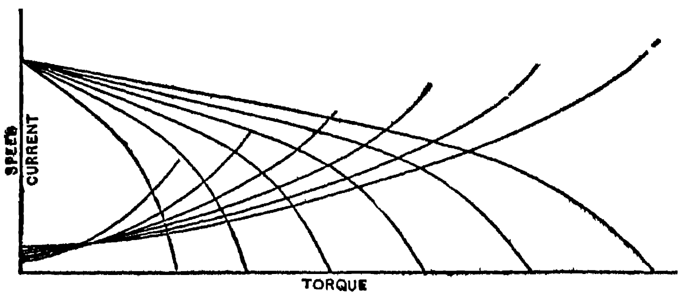


FIG 13—SPEED-TORQUE AND CURRENT-TORQUE CURVES FOR POLYPHASE MOTOR WITH ELECTRO-MOTIVE FORCE VARIED OVER A WIDE RANGE.

have the shape shown in Fig. 14. The motor starts with the desired torque at reduced e. m. f., and comes up to almost rated speed before switching over. This is suitable for constant speed work. In Fig. 14 are shown both the starting and running speed-torque curves, and the currents both in the motor and the line. The line currents are smaller than the motor currents in the ratio of reduction of electro-motive force in the regulating transformers.

SPEED-TORQUE CURVES FOR VARIABLE SPEED WORK

For cranes, elevators, and variable speed work in general, curves of the form shown in Fig. 15 are preferable. The line currents are also shown in this figure. This series of speed-torque

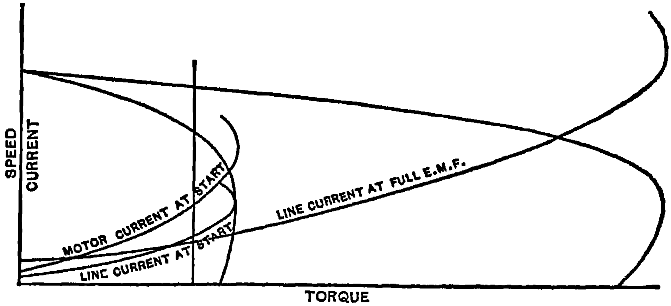


FIG. 14—BEST SHAPE OF SPEED-TORQUE CURVE FOR MOTOR STARTED AND SPEEDED UP WITH A SINGLE REDUCED VOLTAGE, BEFORE BEING TRANSFERRED TO WORKING VOLTAGE.

curves shows that a wide range of speed may be obtained by proper variations of the applied electro-motive force. The line currents "A," "B," etc., practically overlap each other. This means that the line current required with this method of control is very nearly

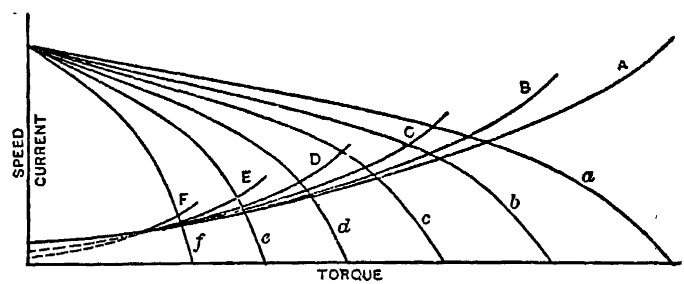


FIG. 15—SPEED-TORQUE AND CURRENT-TORQUE CURVES OF MOTOR FOR CRANES, ELEVATORS AND SIMILAR VARIABLE SPEED WORK WITH VOLTAGE CONTROL. CURVES a, b, c, d, e, f, ARE SPEED-TORQUE CURVES WITH VARIABLE VOLTAGE. CURVES A, B, C, D, E, F, SHOW CORRESPONDING LINE CURRENT.

constant for any given torque, independent of the speed. The same is true of the method of control by varying the secondary resistance. It may be noted that the current for starting, as on curve "C," for instance, is slightly greater than that required for running at the same torque on "B" or "A." This is due to the speed-torque curve being somewhat curved at its outer end. With a somewhat higher resistance of the secondary the curves are more

nearly straight, but the drop in speed is somewhat increased on the speed torque for any given electro-motive force In practice, a compromise is made between the best possible starting condition and a condition of less speed drop.

A comparison of the methods of control by varying the secondary resistance and by varying the applied electro-motive force shows that they give practically the same results in regard to starting, speed regulation, etc. But a motor that has been designed for regulation by varying its secondary resistance, will generally give very poor results when an attempt is made to operate it by the variable electro-motive force method A motor must be especially proportioned for small magnetic leakage when this method of control is to be used. The proportions and the arrangement of the parts are such as may class this as a practically distinct type of motor.

Efficiency and Power Factor

We come now to the other characteristics of the polyphase motor, the most important of which are the efficiency and the power factor. The importance of efficiency is generally appreciated, but the question of power factor in most cases appears to be not thoroughly understood or else is entirely overlooked.

The efficiency of a polyphase motor is the ratio of the power developed to the true power expended, as in any other kind of a machine. The power developed may be obtained from the speed-torque curves. If the torques are given for one foot radius, and the speed in revolutions per minute, then the product of any given torque by the corresponding speed, divided by 5,250, will give the power developed in horse-power; or torque multiplied by speed, divided by seven, gives the power developed in watts. This power, plus the iron, copper and friction losses, gives the true power expended.

The power factor is the ratio of the true power to the apparent power expected. This apparent power is proportional to the products of the primary currents by the electro-motive forces. If there is magnetizing current, and if the motor has magnetic leakage, the primary currents are not in phase with their electro-motive forces and their products represent an apparent power which is greater than the true energy expended. The current of each circuit can be considered as made up of two currents, one of which is in phase with the applied electro-motive force, representing true energy, and the other at right angles to the electro-motive force, representing no energy. The right-angled component is the

one that has an injurious effect on the regulation of the generator, transmission lines, transformers, etc.

The size of this component, compared with the useful current, may be shown by a table:

Power Factor	Total Current	Useful Component	90 Degree Component
100	100	100	0.
99	100	99	14.2
98	100	98	19.9
95	100	95	31.2
90	100	90	43 6
80	100	80	60.0
70	100	70	71 4
60	100	60	80 0
50	100	50	86 6
40	100	40	91 6

Effects of Lagging Current

At 90 percent power factor, for instance, the current that is lagging 90 degrees behind the electro-motive force is equal to 43 6 percent of the total current flowing. This lagging current reacts on the generator, affecting the regulation. In an alternating-current generator, a 90-degree lagging current in the armature coils directly opposes the field magnetization. When delivering a current at 90 percent power factor there is over 43 percent of this current opposing the field, and at 80 percent power factor 60 percent is opposing the field. If the armature ampere turns are normally 20 percent as great as the field ampere turns, then a load of 80 percent power factor will give an opposing magnetization in the armature of about 60 percent of the total armature ampere turns, or about 12 percent of the total field, and the armature electro-motive force will be lowered approximately that percent more than with a load of 100 percent power factor.

The inductive effects of the lagging current in the transmission circuits and transformers are much more serious than those from a current that is in phase with the electro-motive force. The generator, transformers, lines and motors also have increased losses, due to the large current required when the power factor is low. An 80 percent power factor in a system means losses due to heating of conductors more than 50 percent greater than those with 100 percent power factor. These figures indicate the importance of good power factors in an alternating-current system.

Magnetizing Current and Magnetic Leakage Determine Power Factor

The lagging, or 90-degree component, of the current in a motor depends upon the amount of the no-load, or magnetizing, current and upon the magnetic leakage Let this lagging component be expressed in percent of the total current Also express the magnetizing current in percent of the total current, and the total magnetic leakage in percent of the total primary induction. Then the sum of the percents of magnetizing current and magnetic leakage represents very closely the percent of the lagging component of the primary current. If, for example, the magnetizing current is 30 percent and the leakage is 14 percent, the resulting lagging component is about 44 percent. From the preceding table, this indicates about 90 percent power factor A low leakage and a high magnetizing current may give the same power factor at full load as a high leakage and low magnetizing current; but at half load, the percent magnetizing current is practically doubled, while the percent magnetic leakage is halved. Hence, a low magnetizing current is of great importance in maintaining a high power factor If a high value of power factor over a wide range is desired, then both the leakage and the magnetizing current must be low.

Voltage Control versus Rheostatic Control

The method of control by varying the primary electro-motive force is dependent upon the fact that the motor has a low magnetic leakage. By using certain proportions and arrangements of the windings on the primary and secondary, the magnetizing current may be made comparatively low. Thus both conditions for good power factor are obtained.

With the method of control by varying the secondary resistance, good power factors may be obtained. But the form of secondary winding required when variable resistances are used tends to reduce both the power factor and the maximum torque.

Best Form of Secondary Winding

An elaborate series of tests was made to determine the best type of winding for the secondary of a polyphase motor. First, two circuits were arranged to give secondary phases ninety degrees apart. The starting, running and maximum load conditions were determined. Then a three-phase secondary winding was used. This gave a higher pulling-out torque and better power factor than the two-phase Four phases were tried and were better than three; and six were better than four. Then twelve phases were

tried, with a gain over six in maximum torque, but not much gain in efficiency. The power factor was somewhat improved. Finally the winding was completely short-circuited on itself, all coils being connected to a common ring. This gave a further increase in maximum torque and power factor over the preceding arrangement, but there was very little gain in efficiency. The same primary was used in all these tests. Each time the number of secondary circuits was increased the power factor was somewhat improved. This was due to the fact that the secondary currents were able to so distribute themselves that the local electro-motive forces in the coils, due to leakage, were diminished; or, the magnetic leakage may be considered to have been diminished. This would necessarily give higher pulling-out torques and higher-power factors.

Best Form of Primary Windings

Very complete tests were also made to determine the best form of primary winding, and a certain method of distribution of the coils was found to diminish the primary magnetic leakage very considerably. This somewhat increased the maximum torque and the power factor. Utilizing the arrangements of the primary and the secondary windings just described, and otherwise proportioning for small magnetic leakage, a motor may be obtained that has a comparatively low total induction, and yet has a magnetic leakage of but a few percent. The low induction allows a small magnetizing current and comparatively low iron losses. The low leakage gives a high pulling-out torque, and thus allows a good speed regulation, and also good starting conditions, by varying the applied electro-motive force.

Type C Motors

Motors that are adapted for operation under the conditions of variable applied electro-motive forces with constant secondary resistance must have the special forms of speed-torque curves shown in Figs. 12 to 15, and they may therefore be considered as forming a distinct type. This type has received the name Type C. The Type C motor is always characterized by low magnetic leakage and consequent high pulling-out torque. The secondary has no adjustable resistance and all regulation is obtained by varying the adjustable electro-motive force. The secondary is made the rotating part, on account of the type of winding used, which consists of copper bars placed in tunnels or slots in the core and bolted to two end rings. There are no bands, and the question of

insulation is of very little importance for the maximum secondary electro-motive force does not exceed three volts in a 500 horse-power motor and is less with smaller sizes.

Advantages of Type C Motors

This type of motor possesses several distinct advantages over other forms of polyphase motors. The method of control, by varying the electro-motive forces applied to the motor, leads to

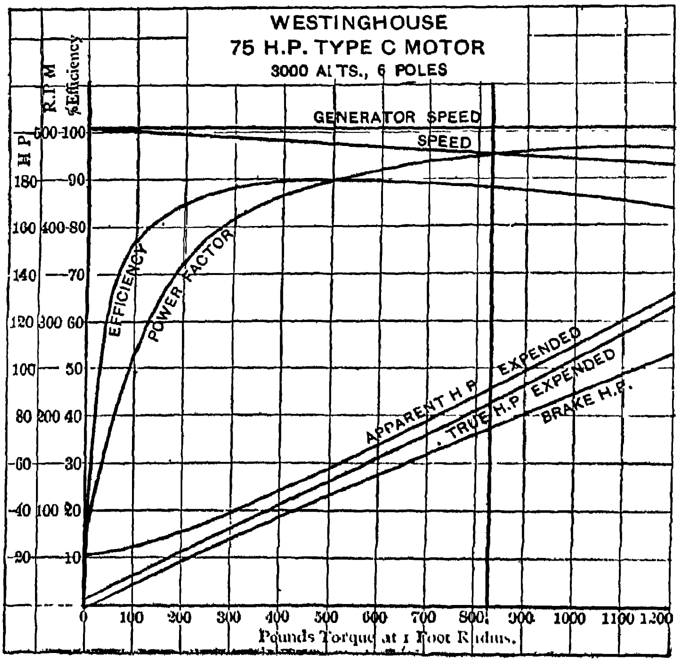


FIG. 16—PERFORMANCE CURVE OF 75 H. P. TYPE C MOTOR

two very important advantages, one of which is mechanical and the other electrical. With this method of control there are no regulating appliances on the motor and, in consequence, it may be of the simplest possible form. The electrical advantage is that the motor may be started and controlled from a distance. Thus it may be placed entirely out of reach of the operator. On traveling cranes, for example, this is of special advantage, for in this case only the primary wires need be run from the operator's cage to the motor. If there are several motors on the crane, there may be one wire common to all the motors and but two additional wires per

motor are required. Thus for the three motors, a minimum of eleven trolley wires may be used.

If the variable electro-motive forces are obtained from transformers, the switches for operating several motors may be wired to one set of transformers and the motors may be started and regulated independently. For traveling cranes, only one set of transformers is used for the hoisting, bridge and traveling motors,

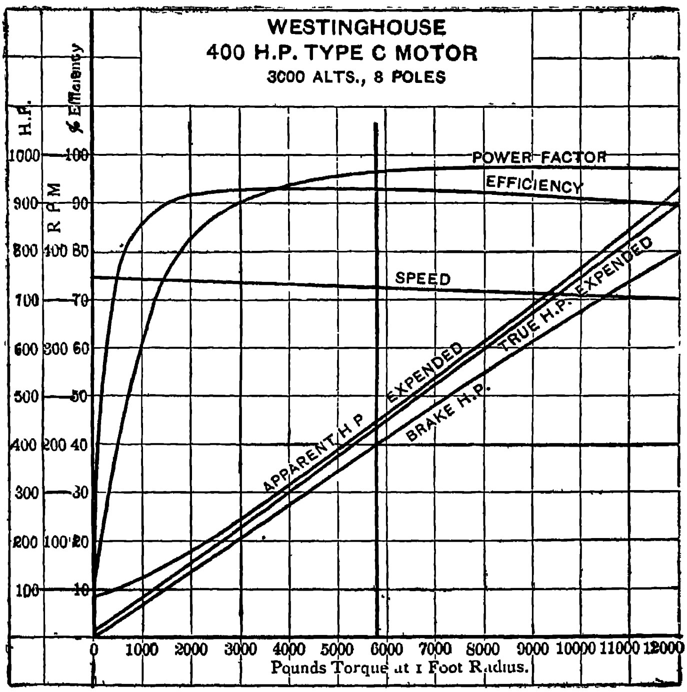


FIG. 17—PERFORMANCE CURVES OF 400 H P. TYPE C MOTOR

and this set may supply currents at different electro-motive forces to all the motors at the same time. A further advantage possessed by this motor lies in the high pulling-out torque. If a heavy overload, or a load having great inertia, is suddenly thrown on a motor that has a speed-torque curve like "A" in Fig. 6, the point of maximum torque may be passed for an instant, and the motor will be stopped unless the load is quickly removed. A Type C motor in this case would have its speed pulled down for a moment, but this reduction in speed gives an increased torque, thus enabling the motor to carry the overload.

If the electro-motive force of the system is suddenly lowered, the pulling-out torque of the motors is lowered very materially. A reduction of twenty percent in the electro-motive force will lower the pulling-out torque to about two-thirds of its former value. Even with a temporary drop in the electro-motive force, such as would be caused by a momentary short-circuit on the lines, this may be sufficient to stop the motor But a motor that has a pulling-out point several times as large as its normal running torque is very rarely in danger of being shut down from this cause. This type of motor has a starting torque from two to four times as large as the full-load running torque and it is thus able to start any kind of load. In practice the starting torque is adjusted to the load to be started by applying a suitable electro-motive force, as will be explained below.

A last, but not least, advantage of the Type C motor is its adaptability for large sizes. The larger the motor of this type, the lower in proportion can be its magnetic leakage and its magnetizing current. In consequence, the power factors are very high. The efficiencies are also very good over a wide range of load The curves for a seventy-five horse-power, six-pole, 3,000-alternation motor are given in Fig. 16, also the curves for a 400-horse-power, 2,300-volt, eight-pole, 3,000-alternation motor in Fig. 17 The power factors of these motors are good examples of what can be obtained on large motors of this type.

Speed Variation with Polyphase Motors

There are six methods of varying the speed of polyphase motors, but some of them are applicable only in special cases. These methods are:

(1)—Varying the number of poles.
(2)—Varying the alternations applied.
(3)—Motors in tandem, or series-parallel.
(4)—Secondary run as single-phase.
(5)—Varying the resistance of the secondary.
(6)—Varying the electro-motive force of the primary, with constant secondary resistance.

Some of these methods are efficient, while some are very inefficient if the speed is to be varied over a wide range.

Varying the Number of Poles

The first method, varying the number of poles, is efficient to a certain extent, but is limited in the number of combinations of

poles obtainable. But if combined with some of the other methods it may be made fairly effective over a wide range. It consists in varying the arrangement of the primary coils in such a way that the number of resulting poles is varied. This may be accomplished by having two or more separate windings on the primary; or one winding may be used, it being rearranged for different speed. With this method of varying the speed, a secondary of the "cage" type is the only practical one. With a "grouped" or "polar" winding on the secondary, this would need rearranging for the different speeds, just as in the case of the primary. But the cage winding, being short-circuited on itself at all points, is adapted to any number of poles. In general, this method of regulation will allow for only two speeds without great complications, and the ratio of the two speeds is preferably two to one, although three to one may be obtained. The simplest arrangement of winding consists of two separate primary windings; one for one number of poles, and the second for the other. In combination with a variable primary electro-motive force, the speed-torque curves being of such shape that this method may be used, the variable-pole method of regulation may be made fairly efficient over a wide range of speed. But the two windings considerably increase the size of the motor, while the one-winding arrangements are rather complicated. Consequently, we may consider that this method of speed variation will be used only in special cases.

Varying the Number of Alternations

The second method, variable alternations, is theoretically the ideal method; but it is practically limited to a few special applications, for we have as yet no commercial alternation transformer.

In a few cases, where but one motor is operated, the generator speed may be varied. If the generator is driven by a water-wheel, its speed may be varied over a wide range, and the motor speed will also vary. If the generator field be held at practically constant strength, then the motor speed may be varied from zero to a maximum at constant torque with a practically constant current. This is a convenient method of operating a motor at a distance from the generator. The speed of the motor may be completely controlled by an attendant at the generating station.

Fig. 18 shows the speed-torque and other curves of a motor when operated at 7200, 3600, 1800 and 720 alternations per minute, or at 100, 50, 25 and 10 percent of the normal alternations. The speed-torque curves, corresponding to the above alternations are,

"a," "b," "c" and "d." The current curves are "A," "B," "C" and "D." This figure shows that for the rated torque "T," the current is practically constant for all speeds, but the electro-motive force varies with the alternations. Consequently, the apparent power supplied, represented by the product of the current by

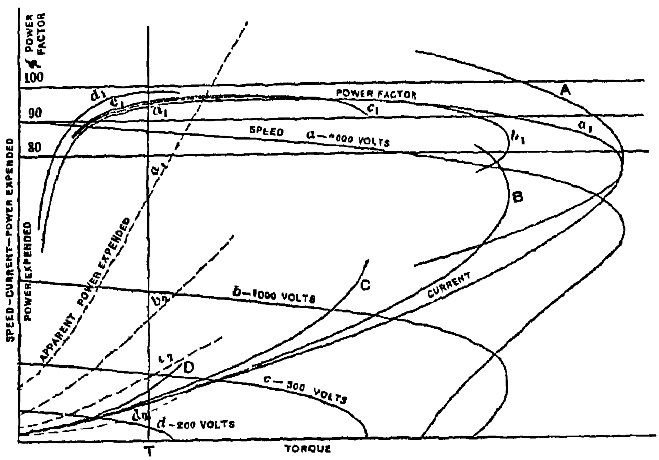


FIG 18—PERFORMANCE CURVES OF POLYPHASE MOTOR WITH DIFFERENT ALTERNATIONS AND ELECTRO-MOTIVE FORCES.

electro-motive force, varies with the speed of the motor, and is practically proportionate to the power developed

MOTORS IN TANDEM OR SERIES-PARALLEL

The third method is to run motors in tandem or series-parallel. In this arrangement, the secondary of one motor is wound with a grouped or polar winding to give approximately the same electro-motive force and number of phases as the primary. The secondary is connected to the primary of a second motor. The secondary of the second motor may be closed on itself, with or without a resistance, or may be connected to the primary of a third motor, etc. The arrangement with two motors is shown in Fig. 19. At start, motor No. 1 receives the full number of alternations on its primary, and its secondary delivers the same number to the primary of motor No. 2. Both motors will start. As motor No. 1 speeds up, its secondary alternations fall. At about one-half speed, its secondary alternations are about one-half its primary, and motor No. 2 receives one-half the alternations of motor No. 1; it also tends to run at half-speed. Therefore, if both motors are

coupled to the same load, this half speed is a position where the two motors tend to operate together. By connecting both primaries across the line, both motors will be run at full speed. Thus, with two motors, two working speeds may be obtained. This method always requires at least two motors. Its application is limited to a few special cases.

Secondary With Only a Single Circuit Closed

The fourth method—the secondary run with a single circuit closed —will give a half-speed, and with two or more circuits closed, will give full speed. But the power factor at the half-speed is very low, and the efficiency is not nearly so good as when run at full speed. This may have a few special applications. Fig 20 shows this arrangement.

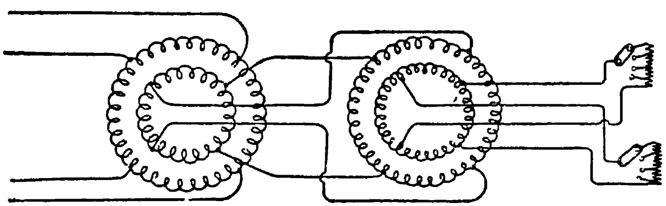


FIG. 19—DIAGRAMMATIC ARRANGEMENT OF THE TWO POLYPHASE MOTORS CONNECTED IN TANDEM OR SERIES PARALLEL

Varying the Resistance of the Secondary

The fifth arrangement is by varying the resistance in the secondary. This method was considered before when the speed-torque characteristics were shown. This will not give constant speed except with constant load, as the speed-torque curve, with a relatively large resistance is a falling curve. At heavy torques, the motor will run at very low speeds, while with light loads it will run at almost full speed. The speed regulation will be similar to that of a direct-current shunt motor with a resistance in circuit with the armature. To hold constant speed with variable load, this resistance requires continual adjustment.

Varying Primary Voltage

The sixth method—that in which the primary electro motive force is varied while the secondary resistance is held constant—gives the same results as the fifth method, as the speed-torque curves are similar. To hold a constant low speed, the electromotive force must be varied continually if the load is changing.

Like the fifth method, it is not efficient at low speeds, as the reduction in speed is obtained by means of a corresponding loss of energy in the secondary circuits.

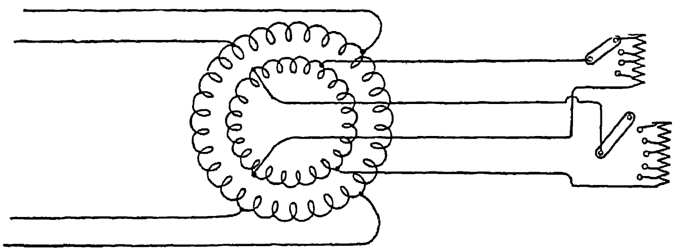


FIG 20—POLYPHASE MOTOR WITH ONLY ONE SECONDARY CURRENT CLOSED

For crane work, hoisting, etc , where it is necessary to run at reduced speed for but a portion of the time, either of the methods five or six is satisfactory, but method five requires the use of a variable secondary resistance, and there must be a set of secondary leads carried out to a rheostat if the speed changes are to be gradual. This introduces complication, especially on a crane where several motors are to be controlled In this case there must be trolley wires for both the primary and the secondary circuits of each motor. But by method six, the control is effected in the primary circuit and only primary trolley wires are needed, and these may be controlled from one pair of transformers, as explained before. The sixth method is therefore the simplest and most practical one to use for hoisting, etc , and will be found to present many advantages for all classes of work, whether speed regulation is important or not.

Method of Varying Primary Electro-Motive Force

There are several methods of varying the electro-motive force applied for starting and varying the speed on the Type C motor. These may be classified under three headings:

(1)—Varying the electro-motive force from the generator.

(2)—Varying the electro-motive force by transformers.

(3)—Varying the motor connections.

Varying Electro-Motive Force from the Generator

A variable electro-motive force may be obtained from the generator in several ways. The generator may be run at low

speed, with the field charged. This gives lower electro-motive force and lower alternations at the same time. This is adapted only to places where all the motors are to be started at once.

The generator may be run at normal speed and its field charge lowered. This gives the normal alternations with lower electro-motive force. This is practicable only where all the motors are to be started at once.

A third method is to so arrange the generator windings that two or more electro-motive forces for each phase may be obtained. A lower electro-motive force may be used at start, and a higher for running.

The different arrangements of the generator windings for this purpose are as follows:

If the armature has but one winding closed on itself, like a direct-current machine, two or three phases may be taken off. For two phases four leads are used. Fig. 21 illustrates this Between

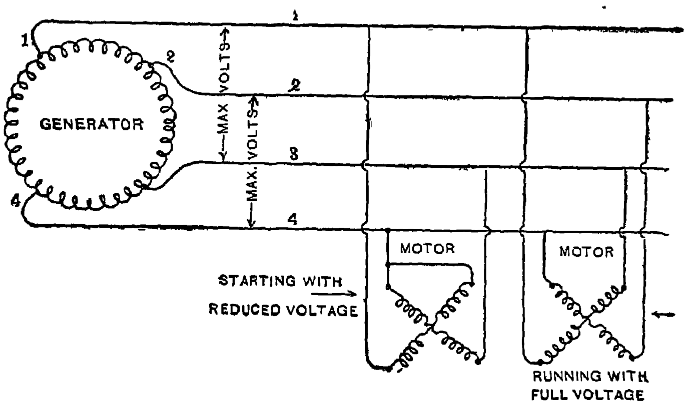


FIG. 21—CONNECTIONS FOR TWO-PHASE MOTORS STARTING ON SIDE CIRCUITS.

1-3 and 2-4 is the maximum electro-motive force, and between 1-2, 2-3, 3-4 and 4-1 there is 0.7 the electro-motive force of 1-3. The electro-motive force 1-2 is at quarter phase to that of 4-1 and 2-3, and the electro-motive force 3-4 is at quarter phase to that of 2-3 and 4-1. Therefore, across any two adjacent side circuits we have quarter phase circuits of 0.7 the electro-motive force of the main circuit. A motor may thus be started on any adjacent side circuit and then switched to the main circuit. This method is well adapted for local plants where the generator electro-motive force is 200 or 400 volts. If there are many motors to be started, and

the starts are numerous, it is advisable to wire the starting switches so that the various motors are started on different side circuits.

If the generator winding is of the "open coil" type, a similar arrangement may be obtained for two phases The two windings may be connected to the middle point, thus giving side circuits of 0.7 electro-motive force This is shown in Fig 22.

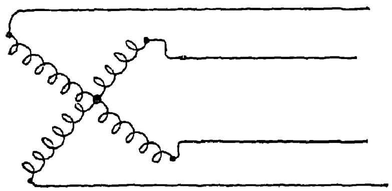


FIG 22—WINDINGS OF "OPEN COIL," TWO-PHASE GENERATORS CONNECTED TOGETHER AT MIDDLE POINT TO ALLOW STARTING OF MOTORS FROM "SIDE CIRCUITS".

Three-phase connections do not allow any convenient combinations with the generator winding. A fourth wire may be run, however, which will give about 0 58 electro-motive force for starting.

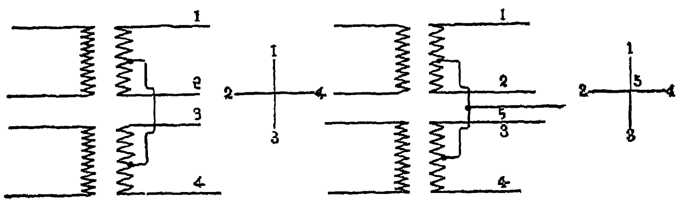


FIG 23—CONNECTIONS OF TRANSFORMERS ON TWO-PHASE CIRCUITS TO GIVE .7 AND .5 NORMAL VOLTAGE FOR STARTING MOTORS

Variable Electro-Motive Force from Transformers

The method of varying the electro-motive force by means of transformers admits of many different combinations. Several of the simpler forms will be given.

(1) The transformers may be so connected that two or more electro-motive forces may be obtained.

For two-phase circuits, the secondaries may be connected together at the centre, as shown in Fig. 23 This gives two main circuits, and four side circuits of lower electro-motive force If an extra wire be carried out from the point 5, then 1-5, 2-5, will form a two-phase combination for 0 5 voltage, while 1-2, 2-3 form a

two-phase combination for 0.7 voltage, and 1-3 and 2-4 give full voltage.

Another method is to connect the secondaries at one side of the centre, as shown in Fig. 24. Then 3-5 and 4-5 give one electro-motive force; 1-5 and 2-5 give a higher electro-motive force, and 1-3 and 2-4 give full electro-motive force.

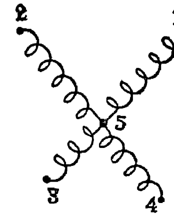


FIG. 24—CONNECTIONS OF SECONDARIES OF TRANSFORMERS ON TWO-PHASE CIRCUIT AT A POINT ONE SIDE OF THE CENTER, TO OBTAIN LOWER ELECTRO-MOTIVE FORCES FOR STARTING MOTORS.

These combinations are useful in certain cases, but are not as general in their application as the following method.

(2) Auto-transformers with loops brought out for lower electro-motive forces.

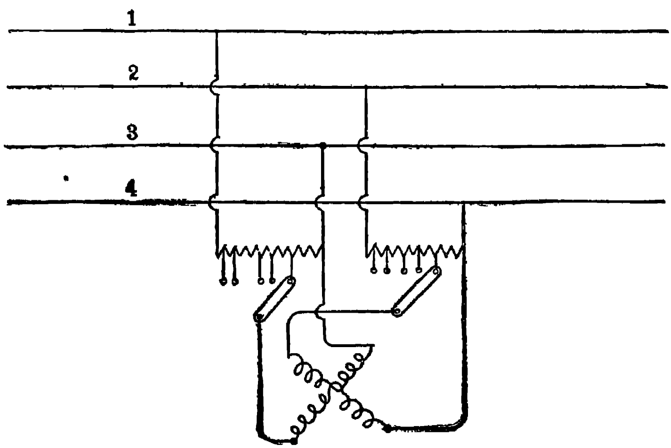


FIG. 25—DIAGRAMMATIC ARRANGEMENT OF AUTO-TRANSFORMERS AND CONTROLLERS FOR REGULATING SPEED OF TWO-PHASE MOTOR BY VARIANCES OF VOLTAGE.

In this method, no special combinations of the lines, lowering transformers or generators are made, but, in connection with each motor, a small pair of auto, or one-coil transformers, is used for

auto-transformers are made larger From these auto-transformers several loops or connections are brought out. For regulating the speed these are connected to the contact plates or dials of a controller, as shown in Figs 25 and 26 But for starting purposes only, when but one loop from each transformer is used, a pair of switches

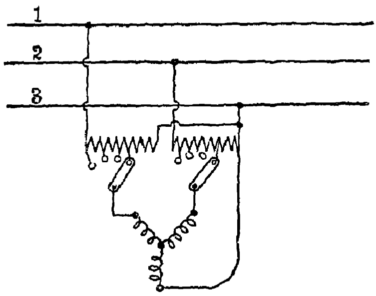


FIG 26—DIAGRAMMATIC ARRANGEMENT OF AUTO-TRANSFORMERS AND CONTROLLER FOR REGULATING SPEED OF THREE-PHASE MOTOR BY VARYING THE VOLTAGE

are used in connection with the transformers. With the switches open, the motor is disconnected. Throwing one direction starts the motor at reduced voltage and brings it up to almost full speed. The switches are then thrown over to full electro-motive force.

Two small transformers in a case with one four-jaw, throw-over switch, form what is called an "auto-starter." This is readily arranged for either two or three-phase circuits and motors. This makes a most flexible arrangement for starting, as the motor may be put at any location, and the auto-starter may be put in the most convenient position. It also loads all the line wires equally at start, and each motor and starter really form a unit separate from all the others One pair of transformers may be connected to several sets of switches and thus be used for starting several motors.

Where motors are close to reducing transformers, the secondaries of the transformers may have loops brought out, to which one or more switches are connected. The primaries of the transformers may have loops connected to proper switches, and the number of primary turns in the circuit may be varied instead of the secondary. This is applicable when the transformers supply only one motor, or when several motors are started at the same time. A regulator with secondary movable with respect to the primary may be used Regulators of this type vary the electro-

motive forces without any "make" or "break" devices, and consequently have no sparking tendency. But they are in general too complicated and costly to compete with the transformer with loops.

Varying the Motor Connections

This is not a method for changing the electro-motive force applied, but for varying the number of turns in series with a given electro-motive force, and the effect is the same as varying the applied electro-motive force. This method is rather limited in its application owing to the complication involved. The simplest case for two-phase motors is a series-parallel combination of the windings of each phase. This is equivalent to using 0.5 electro-motive force at start. For three-phase motors, series-parallel may be used or the winding may be thrown from the star system of connection at start to the delta system for running. This is equivalent to using about 0.6 electro-motive force for start. But, as the star connection is preferred for the running condition, this combination is not advisable.

Choke Coils or Resistance in the Primary

There is a fourth method of regulation which may be mentioned, but which is not advisable in general practice. This is the use of choke coils or resistance in the primary circuits of the motor, to reduce the electro-motive force. These really give varying electro-motive forces. With choke coils, the power factor at start is lowered, with correspondingly bad effect on the generator and system. With ohmic resistance in the primary circuit, the reduction of electro-motive force is accompanied by a consumption of energy in the primary circuit which in no way represents torque.

WASHINGTON, BALTIMORE & ANNAPOLIS SINGLE-PHASE RAILWAY

FOREWORD—This paper was presented before the American Institute of Electrical Engineers, September, 1902. It was the very first information given out for publication regarding the single-phase alternating-current railway system as developed and installed so extensively since that time.

Before the publication of this paper, it was generally assumed that the difficulties in the commutation of alternating current were so great that only motors of relatively small capacity could be built. Following its publication, many of the larger companies throughout the world began work on such motors and produced operating railway equipments with more or less success —(ED.)

THE Washington, Baltimore and Annapolis Railway is a new high-speed electric line extending from the suburbs of Washington to Baltimore, a distance of about 31 miles, with a branch from Annapolis Junction to Annapolis, a distance of about 15 miles. The overhead trolley will be used, and schedule speeds of over 40 miles per hour are to be attained. This road is to be the scene of the first commercial operation of an entirely new system of electric traction.

The special feature of this system is the use of single-phase alternating current in generators, transmission lines, trolley car equipment and motors It constitutes a wide departure from present types of railway apparatus. The standard D. C. railway equipment possesses several characteristics which fit it especially for railway service. These characteristics have been of sufficient importance to overbalance many defects in the system. In fact, a far greater amount of effort and engineering skill has been required for overcoming or neutralizing the defects, than for developing the good features possessed by the system. By far the most important characteristic possessed by the D. C. system is found in the type of motor used on the car. The D. C. railway motor is in all cases a series-wound machine. The series motor is normally a variable field machine and it is this feature which has adapted the motor especially to railway service. Shunt-wound motors have been tried and abandoned. All manner of combinations of shunt,

series and separate excitation have been devised and found wanting, and in many cases the real cause of failure was not recognized by those responsible for the various combinations. They all missed to a greater or less extent the variable-field feature of the straight series motor. It is true that a variable field can be obtained with shunt or separate excitation, but not without controlling or regulating devices, and the variation is not inherently automatic, as in the series motor Polyphase and single-phase induction motors do not possess the variable field feature at all, as they are essentially constant-field machines They are equivalent to direct current shunt or separately excited motors with constant field strength, which have been unable to compete successfully with the series motor The variable field of the series motor makes it automatically adjustable for load and speed conditions. It also enables the series motor to develop large torques without proportionately increased currents The automatically varying field is accompanied by corresponding variations in the counter e.m f. of the armature, until the speed can adjust itself to the new field conditions This feature is of great assistance in reducing current fluctuations, with a small number of steps in the regulating rheostat Any increase in current, as resistance is cut out, is accompanied by a momentary increase in the counter e.m f, thus limiting the current increase to a less value than in the case of constant field motor

Next to the type of motor, the greatest advantage possessed by the D. C. system lies in the use of a single current or circuit, thus permitting the use of one trolley wire The advantages of the single trolley are so well-known that it is unnecessary to discuss them For third rail construction, the use of single current is of even greater importance than in the case of overhead trolley It is seen, therefore, that it is not to the direct current that credit should be given for the great success of the present railway system, but to the series type of motor and the fact that up to the present time no suitable single-phase A C. motor has been presented

Some of the undesirable features of the D C railway system should also be considered. The speed control is inefficient. A nominally constant voltage is supplied to the car, and speed control is obtained by applying variable voltage at the motor terminals This variation is produced by the use of resistance in series with the motors, with a loss proportional to the voltage taken up by the resistance By means of the series-parallel

arrangement, the equivalent of two voltages is obtainable at the motor terminals without the use of resistance. Therefore, with series-parallel control, there are two efficient speeds with any given torque, and with multiple control there is but one efficient speed with a given torque All other speeds are obtained through rheostatic loss, and the greater the reduction from either of the two speeds, series or parallel, the lower will be the efficiency of the equipment. At start, the rheostatic losses are always relatively large, as practically all the voltage of the line is taken up in the rheostat For heavy railroad service, where operation for long periods at other than full and half speeds may be necessary, the rheostatic loss will be a very serious matter.

The controlling devices themselves are also a source of trouble. An extraordinary amount of time and skill has been expended on the perfection of this apparatus The difficulties increase with the power to be handled The controller is a part of the equipment which is subjected to much more than ordinary mechanical wear and tear, and it can go wrong at any one of many points. The larger the equipment to be controlled, the more places are to be found in the controller which can give trouble. The best that can be said of the railway controller is that it is a necessary evil.

Another limitation of the D. C. system is the trolley voltage Five hundred volts is common at the car and 650 volts is very unusual. By far the larger number of the railway equipments in service to-day are unsuited for operation at 600 volts, and 700 volts in normal operation would be unsafe for practically all The maximum permissible trolley voltage is dependent upon inherent limitations in the design of motors and controllers The disadvantages of low voltage appear in the extra cost of copper and in the difficulty of collecting current. In heavy railroad work the current to be handled becomes enormous at usual voltages. A 2400 h p. electric locomotive, for example, will require between 3000 and 4000 amperes at normal rated power and probably 6000 to 8000 amperes at times. With the overhead trolley these currents are too heavy to be collected in the ordinary manner, and it is a serious problem with any form of trolley or third rail system which can be used. It is evident that for heavy service, comparable with that of large steam railways, a much higher voltage than used in our present D. C. system is essential, and the use of higher voltage is destined to come, provided it is not attended by complications which more than

overbalance the benefits obtained. A further disadvantage of the D. C. system is the destructive action known as electrolysis This may not be of great importance in interurban lines, chiefly because there is nothing to be injured by it. In city work its dangers are well-known, and very expensive constructions are now used to eliminate or minimize its effects.

From the above statements it is evident that an A C railway system, to equal the D. C., should possess the two principal features of the D. C. system, viz A single supply circuit and the variable field motor, and to be an improvement upon the D. C. system, the A. C. should avoid some of the more important disadvantages incident to the present D. C. railway apparatus.

The system must, therefore, be single-phase. The importance of using single-phase for railway work is well known The difficulties and complications of the trolley construction are such that several A. C. systems have been planned on the basis of single-phase supplied to the car, with converting apparatus on the car to transform to direct current. in order that the standard type of railway motors may be used Such plans are attempts to obtain the two most valuable features of the present D C. system. The polyphase railway system, used on a few European roads, employs three currents, and therefore does not meet the above requirement. The motor for the A C railway service should have the variable speed characteristics of the series D. C. motor. The polyphase motor is not suitable, as it is essentially a constant field machine, and does not possess any true variable speed characteristics. Therefore it lacks both of the good features of the D. C. railway system. A new type of motor must, therefore be furnished, as none of the alternating current motors in commercial use is adapted for the speed and torque requirements of first-class railway service. Assuming that such a motor is obtainable for operation on a single-phase circuit, the next step to consider is whether the use of alternating instead of direct current on the car, will allow some of the disadvantageous features of the D. C. system to be avoided. The D. C. limits of voltage are at once removed, as transformers can be used for changing from any desired trolley voltage to any convenient motor voltage. Electrolysis troubles practically disappear. As transformers can be used, variations in supply voltage are easily obtainable. As the motor is assumed to have the characteristics of the direct-current series motor, speed control without rheostatic loss is practicable when voltage control is

obtained. This combination, therefore, allows the motor to operate at relatively good efficiency at any speed within the range of voltage obtained If the voltage be varied over a sufficiently wide range, the speed range may be carried from the maximum desired down to zero, and therefore, down to starting conditions. With such an arrangement no rheostat need be used under any conditions, and the lower the speed at which the motor is operated, the less the power required from the line. The least power is required at start, as the motor is doing no work and there is no rheostatic loss. The losses at start are only these in the motor and transforming apparatus, which are less than when running at full speed with an equal torque. Such a system, therefore, permits maximum economy in power consumed by motor and control. This economy in control is not possible with the polyphase railway motor, as this motor is the equivalent of the D. C. shunt motor, with which the rheostatic loss is even greater than with the series motor.

The use of alternating current on the car allows voltage control to be obtained in several ways. In one method a transformer is wound with a large number of leads carried to a dial or controller drum. The Stillwell regulator is a well-known example of this type of voltage control. This method of regulation is suitable for small equipments with moderate currents to be handled. The controller will be subject to some sparking, as in the case of D. C. apparatus, and therefore becomes less satisfactory as the car equipment is increased in capacity. Another method of control available with alternating current is entirely non-sparking, there being no make-and-break contacts. This controller is the so-called "induction regulator," which is a transformer with the primary and secondary windings on separate cores. The voltage in the secondary winding is varied by shifting its angular position in relation to the primary. With this type of voltage controller, very large currents can be handled, and it is especially suitable for heavy equipments, such as locomotives It is thus seen that there is one method of control, available with alternating current, which avoids the troubles inherent to the D. C. controller. The induction regulator is primarily a transformer, and all wear and tear is confined to the supports which carry the rotor. Therefore the objectionable controller of the standard D. C. system can be eliminated, provided a suitable A. C. motor can be obtained. This ideal type

of controller is not applicable to the polyphase railway motor, in which speed control can be obtained only through rheostatic loss. The polyphase control system is even more complicated than the D. C., as there must be a rheostat for each motor, and two or three circuits in each rheostat It is thus apparent that by the use of single-phase alternating current with an A. C motor having the characteristics of the D C. series motor, the best features of the D C. system can be obtained, and at the same time many of its disadvantages can be avoided.

This portion of the problem therefore resolves itself into the construction of a single-phase motor having the characteristics of the D C. series motor There are several types of single phase A. C. motors which have the series characteristics. One type is similar in general construction to a D. C. motor, but with its magnetic circuit laminated throughout, and with such proportions that it can successfully commutate alternating current Such a motor is a plain series motor, and can be operated on either alternating or direct current and will have the same torque characteristics in either case. Another type of motor is similar in general construction to the above, but the circuits are arranged in a different manner. The field is connected directly across the supply circuit, with proper control appliances in series with it. The armature is short-circuited on itself across the brushes, and the brushes are set at an angle of approximately 45° from the ordinary neutral point The first of these two types of motors is the one best adapted for operation in large units.

This is the type of motor which is to be used on the Washington Baltimore and Annapolis Railway. Several motors have been built and tested with very satisfactory results, both on the testing stand and under a car. The results were so favorable that the system was proposed to the Cleveland Engineering Company, representing the Washington, Baltimore and Annapolis Railway, and after investigation by their engineers, the system was adopted. A description of the apparatus to be used on this road will illustrate the system to good advantage.

Single-phase alternating current will be suppled to the car at a frequency of 16⅔ cycles per second, or 2,000 alternations per minute. The current from the overhead trolley wire is normally fed in by one trolley at approximately 1,000 volts. Within the limits of the District of Columbia two trolleys are employed, as by Act of Congress the use of rails as conductors is prohibited in this District, presumably on account of electrolysis. In this

case the trouble, of course, will not exist, but the contracting company has been unable to obtain permission for the grounded circuit.

The alternating current to the car is carried through a main switch or circuit breaker on the car, to an auto-transformer connected between the trolley and the return circuit. At approximately 300 volts from the ground terminal, a lead is brought out from the auto-transformer and passes through the regulator to one terminal of the motors. For starting and controlling the speed, an induction regulator is used with its secondary winding in series with the motors. This secondary circuit of the regulator can be made either to add to, or substract from the transformer voltage, thus raising or lowering the voltage

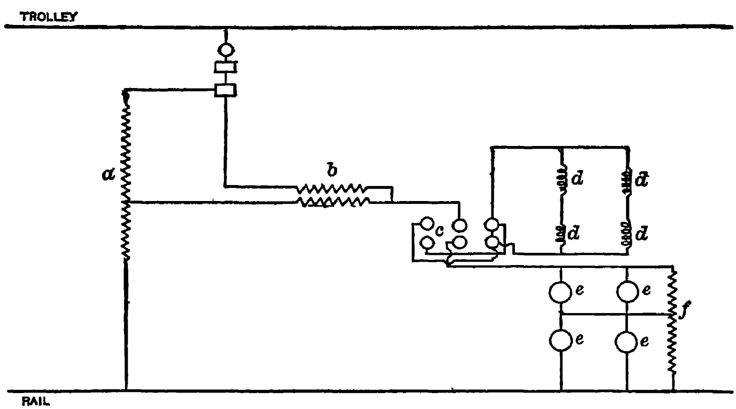


FIG. 1 —*a* Auto-Transformer *b*. Induction Regulator *c* Reversing Switch. *d* Field of Motors *e* Armature of Motors *f* Equalizing Transformer.

supplied to the motors. The regulator therefore does double duty. The controller for D. C. motors merely lowers the voltage supplied to the motors but cannot raise it, but an A. C. regulator can be connected for an intermediate voltage, and can either raise or lower the motor voltage. In this way the regulator can be made relatively small, as it handles only the variable element of the voltage and the maximum voltage in the secondary winding is but half of the total variation required.

In the equipments in question, the range of voltage at the motor is to be varied from approximately 200 volts up to 400 volts or slightly higher. The transformer on the car will supply 315 volts, and the secondary circuit of the regulator will be

wound to generate slightly more than 100 volts when turned to the position of its maximum voltage. This voltage of the regulator is about one-fourth of that of the motors at full voltage. The regulator can consequently be made relatively small, in comparison with the motor capacity of the equipment. It has been found unnecessary to use much lower than 200 volts in this installation, as this voltage allows a comparatively low running speed, and approximately 200 volts will be necessary to start with the required torque The greater part of this voltage is required to overcome the e m f. of self-induction in the motor windings, which is dependent upon the current through the motor and is independent of the speed of the armature.

There will be four motors of 100 h.p. on each car The full rated voltage of each motor is approximately 220 volts The motors are arranged in two pairs, each consisting of two armatures in series, and two fields in series, and the two pairs are connected in parallel The motors are connected permanently in this manner As voltage control is used, there is no necessity for series parallel operation, as with D. C. motors. To ensure equal voltage to the armatures in series, a balancing or equalizing action is obtained by the use of a small auto-transformer connected permanently across the two armatures in series with its middle point connected between them. The fields are arranged in two pairs, with two fields in series and two pairs in multiple This parallels the fields independently of the armatures, which was formerly the practice with D C motors. It was a defective arrangement with such motors, as equal currents in the field did not ensure equal field strengths in the motors, and the armatures connected in parallel would be operating in fields of unequal strength, with unequal armature currents as a direct result. With alternating currents in the fields, the case is different The voltage across the fields is dependent upon the field strengths, and the current supplied to the fields naturally divides itself for equal magnetic strengths The chief advantage in paralleling the fields and armatures independently is, that one reversing switch may serve for the four motors and one balancing transformer may be used across the two pairs of armatures The usual D. C. arrangement of armatures in series with their own fields can be used, with a greater number of switches and connections.

The general arrangement of the auto-transformer, regulator, motors, etc , is shown in Fig. 1

The induction regulator or controller, resembles an induction motor in general appearance and construction. The primary winding is placed on the rotor, and the secondary or low voltage winding on the stator. The rotor also has a second winding which is permanently short-circuited on itself. This function of this short-circuited winding is to neutralize the self-induction of the secondary winding as it passes from the magnetic influence of the primary. The regulator is wound for two poles, and therefore is operated through 180° for producing the full range of variation of voltage for the motors. One end of the primary winding of the regulator is connected to the trolley, and the other to a point between the regulator and the motors. It thus receives a variable voltage as the controller is rotated. There are several advantages in this arrangement of the primary in this particular case. First, the regulator is worked at a higher induction at start, and at lower induction when running, the running position being used in these equipments for much longer periods than required for starting Second, when the motors are operating at full voltage the current in the primary of the regulator passes through the motors but not through the auto-transformer or the secondary of the regulator. This allows considerable reduction in the size of auto-transformer and regulator. The motors on the car are all of the straight series type. The armature and fields being connected in series, the entire current of the field passes through the armature as in ordinary series D C. motors. The motor has eight poles, and the speed is approximately 700 revolutions at 220 volts. The general construction is similar to that of a D. C. motor, but the field core is laminated throughout, this being necessary on account of the alternating magnetic field. There are eight field-coils wound with copper strap, and all connected permanently in parallel. The parallel arrangement of field-coils assists in the equalizing of the field strength in the different poles, due to the balancing action of alternating circuits in parallel. This arrangement is not really necessary, but it possesses some advantages and therefore has been used. With equal magnetic strength in the poles, the magnetic pull is equalized even with the armature out of center. The armature is similar in general construction to that of a D. C. motor. The fundamental difficulty in the operation of a commutator type of motor, on single-phase alternating current lies in the sparking at the brushes. The working current passing through the motor should be practically no more difficult

to commutate than an equal direct current, and it is not this current which gives trouble. The real source of trouble is found in a local or secondary current set up in any coil, the two ends of which are momentarily short-circuited by a brush. This coil encloses the alternating magnetic field, and thus becomes a secondary circuit of which the field-coil forms the primary. In

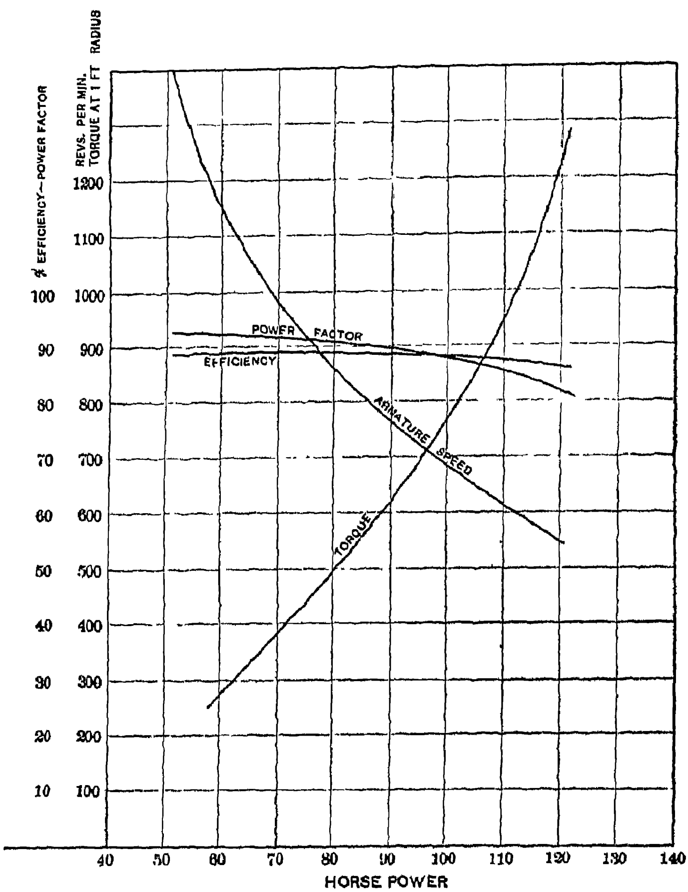


FIG 2 —Westinghouse Alternating Current Railway Motor No. 91.—Single-Phase —220 Volts.

the motors of the Washington, Baltimore and Annapolis Railway, this commutation difficulty has been overcome by so constructing the motor that the secondary or short-circuit current in the armature coil is small, and the commutating conditions so

perfect that the combined working and secondary currents can be commutated without sparking. This condition being obtained, the motor operates like a D. C. machine and will give no more trouble at the commutator than ordinary D. C. railway motors. Experience covering a considerable period in the operation of motors of 100 h.p. capacity indicates that no trouble need be feared at the commutator.

An extended series of tests were made at the Westinghouse shops at East Pittsburg, both in the testing room and under a car. Fig. 2 shows curves of the speed, torque, efficiency and power factor plotted from data from brake tests.

It should be noted that the efficiency is good, being very nearly equal to that of high-class D. C. motors. The power factor, as shown in these curves, is highest at light loads and decreases with the load. This is due to the fact that the power developed increases approximately in proportion to the current, while the wattless component of the input increases practically as the square of the current. The curve indicates that the average power factor should be very good. The calculations for the W. B. and A. Railway show that the average power factor of the motors will be approximately 96 per cent.

The average efficiency of these equipments will be much higher during starting and acceleration than that of corresponding D. C. equipments, and rheostatic losses are avoided. When running at normal full speed, however, the efficiency will be slightly less than with D. C. This is due to the fact that the A. C. motor efficiency is slightly lower than the D. C., and in addition there are small losses in the transformer and the regulator. The A. C equipments are somewhat heavier than the D. C., thus requiring some extra power, both in accelerating and at full speed. Therefore, for infrequent stops the D. C. car equipment is more efficient than the A. C., but for frequent stops the A. C. shows the better efficiency. Tests on the East Pittsburg track verified this conclusion. But the better efficiency of the D. C. equipment with infrequent stops is offset with the A. C. by decreased loss in the trolley wire, by reason of the higher voltage used, and the elimination of the rotary converter losses. The resultant efficiency for the system will therefore be equal to or better than that of the D. C.

In the W. B. and A Railway contract the guarantee given by the Westinghouse Electric and Mfg. Co. states that the efficiency of the system shall be equal to that of the D. C. system with rotary converter substations

There is one loss in the A. C. system which is relatively much higher than in the D C This is the loss in the rail return. Tests have shown that at 2,000 alternations this is three to four times as great as with an equal direct current This would be a serious matter in cases where the D. C rail loss is high. But the higher A. C trolley voltage reduces the current so much, that the A. C. rail loss is practically the same as with direct current at usual voltages In many city railways the D. C. rail loss is made very low, not to lessen waste of power, but in order to reduce electrolysis. In such cases the A. C. rail loss could be higher than D. C, thus decreasing the cost of return conductors. More frequent transformer substations, with copper feeders connected to the rails at frequent intervals will enable the rail loss to be reduced to any extent desired. As a frequency of 2,000 alternations per minute is used, the lighting of the cars and the substations was at first considered to be a serious difficulty, due to the very disagreeable winking of ordinary incandescent lamps at this frequency. Two methods of overcoming the winking were tried, both of which were successful. One method was by the use of split phase. A two-phase induction motor was run on a single-phase 2,000 alternating circuit, and current was taken from the unconnected primary circuit of the motor. This current was, of course, at approximately 90° from the current of the supply circuit. A two-phase circuit was thus obtained on the car. Currents from the two phases were put through ordinary incandescent lamps, placed close together. The resulting illumination a few feet distant from the lamps showed about the same winking as is noticed with 3,000 alts. With two filaments in one lamp the winking disappears entirely. A three-phase arrangement would work in the same way.

A much simpler method was tried which worked equally well. This consisted in the use of very low-voltage lamps. Low voltage at the lamp terminals allows the use of a thick filament with considerable heat inertia. Tests were made on lamps of this type at a frequency of 2,000 alts., and the light appeared to be as steady as that from the ordinary high-frequency incandescent lamp. The low voltage is not objectionable in this case, as a number of lamps can be run in a series, as in ordinary street railway practice, and any voltage desired can readily be obtained, as alternating current is used on the car.

There will be an air compressor, driven by a series A. C. motor, on each car, for supplying air to the brakes and for operating

the driving mechanism of the controller. The details of this mechanism are not near enough to completion to permit a description of it The method used will be one which readily allows operation on the multiple-unit system.

The generating station contains some interesting electrical features, but there is no great departure from usual A. C. practice. There will be three 1,500 k w. single-phase alternators. These are 24-pole machines operating at 83 revolutions and wound for 15,000 volts at the terminals. They are of the rotating field type, with laminated magnetic circuits and field-coils of strap on edge. The field-coils are held on the pole-tips by copper supports, which serve also as dampers to assist in the parallel running The armatures are of the usual slotted type. The armature coils are placed in partially closed slots. There are four coils per pole The proportions of these machines are such that good inherent regulation is obtained without saturation of the magnetic circuit. The rise in potential with non-inductive load thrown off will be approximately 4 per cent. An alternative estimate was furnished for the generators proposing 20,000 volts instead of 15,000. The simplicity of the type of winding used, and the low frequency, are both favorable for the use of very high voltage on the generator. As 15,000 volts was considered amply high for the service, the engineers for the railway considered it unadvisable to adopt a higher voltage.

There are to be two exciters, each of 100 k w. capacity at 250 revolutions The exciters are wound for 125 volts normal. The armature of each exciter has, in addition to the commutator, two collector rings, so that single-phase alternating current can be delivered It is the intention to use the exciters as alternators for supplying current to the system for lighting when the large generators are shut down at night. The main station switchboard comprises three generator panels, one load panel, and three feeder panels. High-tension oil-break switches are to be provided, operated by means of controlling apparatus on the panels. The switches, bus-bars and all high-tension apparatus will be in brick compartments separate from the board. In each generator circuit there are two non-automatic oil-break switches in series; and on each feeder circuit there are two overload time-limit oil-break switches in series. The two oil-break switches in series on the same circuit can be closed separately and then opened to test the switches without closing the circuit. With the switches in the closed position they are both operated

at the same time by the controller, to ensure opening of the circuit, and to put less strain on the switches, although either one is capable of opening the load There will be nine transformer substations distributed along the railway line. Each station will contain two 250 k.w. oil-cooled lowering transformers, supplying approximately 1,000 volts to the trolley system. The transformers are used in each station so that in case of accident to one transformer the station will not be entirely crippled. It is the intention of the railway company to operate a D. C. road already equipped with the direct-current system The present D. C car equipments are to be retained, but the current will be supplied from a rotary converter substation fed from the main system of the W B and A. Railway. As this system is single-phase, it is necessary that single-phase rotaries be used in the substations. There are to be two k.w. 550-volt rotary converters. These are 4-pole, 500-revolution machines. The general construction of these machines is very similar to that of the Westinghouse polyphase rotary converters. The armature resembles that of a polyphase rotary except in the number of collector rings, and in certain details of the proportions made necessary by reason of the use of single-phase. The commutating proportions are so perfect that any reactions due to the use of single-phase will result in no injurious effect. The field construction is similar to that of a polyphase rotary. The laminated field-poles are provided with dampers of the "grid" or "cage" type, a form used at present in the Westinghouse polyphase rotary converters. This damper serves to prevent hunting, as in the polyphase machines, and also to damp out pulsations due to single-phase currents in the armature. The damper acts to a certain extent as a second phase. Each rotary converter is started and brought to synchronous speed by a small series A. C. motor on the end of the shaft. The voltage at the motor terminals can be adjusted either by loops from the lowering transformer or by resistance in series with the motor, so that true synchronous speed can be given to the rotary converter, before throwing it on the A. C. line.

From the preceding description of this system and the apparatus used on it, some conclusions may be drawn as to the various fields where it can be applied to advantage. It is evident that a good field for it will be on interurban long-distance lines such as the W B. and A. Railway. On such railways, high trolley voltage and the absence of converter substations are very important factors.

For heavy railroading also, this system possesses many ideal features.. It allows efficient operation of large equipments at practically any speed and any torque, and also avoids the controller troubles which are ever present with large direct current equipments. It. also permits the use of high trolley voltage, thus reducing the current to be collected In this class of service the advantages of this A C system are so great that is it possible that heavy railroading will prove to be the special field for it.

For general city work, this system may not find a field for some time to come, as the limitations in the present system are not so great that there will be any great necessity for making a change. It is probable that at first this system will be applied to new railways, or in changing over steam roads rather than in replacing existing city equipments. One difficulty with which the new system will have to contend, is due to the fact that the A. C equipments cannot conveniently operate on existing city lines, as is the present practice where interurban lines run into the cities. It will be preferable for the A. C. system to have its own lines throughout, unless very considerable complication is permitted. When the A. C. system applied to interurban and steam railway systems finally becomes of predominant importance, it is probable that the existing D. C. railways will gradually be changed to A. C. as a matter of convenience in tying the various railway systems together

As was stated above, A. C equipments cannot conveniently be operated on direct current lines. It does not follow that the motor will not operate on direct current. On the contrary, the motor is a first-class direct current machine, and if supplied with suitable control apparatus and proper voltage it will operate very well on the D. C. lines. This would require that the motors be connected normally in series, as the voltage per motor is low. A complete set of D. C. control apparatus would be needed when the A. C. equipment is to be run on direct current, and considerable switching apparatus would be necessary for disconnecting all the A. C. control system and connecting in the D. C. The complication of such a system may be sufficient to prevent its use, at least for some time to come

In some cities, very strict laws are in force in regard to the voltage variations in various parts of the track system. The permissible variations are so small in some cases, that an enormous amount of copper is used for return conductors; and in

some cases special boosters are used in the return circuits to avoid large differences of potential between the various parts of the track system. The object in limiting the conditions in this manner is to avoid troubles from electrolysis. The A. C. system will, of course, remedy this.

For city work, it is probable that voltages of 500 or 600 would be employed instead of 1,000 or higher. The transformers and controllers can be designed to be readily changed from full to half voltage, so that low voltage can be used on one part of the line and high voltage on another As the car equipments of such railways are usually of small capacity, it is probable that speed control will be obtained by means of a transformer with a large number of leads carried out to a control drum, rather than by means of the induction regulator, as the latter device is much more expensive in small units. This is chiefly a question of cost, and if the advantages of the induction regulator are found to over-weigh the objection of high first cost, then it will be used even on small equipments.

In the W. B. and A. Railway, the generators are wound for single-phase. In the case of large power-stations with many feeders, the generators may be wound for three-phase, with single-phase circuits carried out to the transformer substation, or three-phase transmission may be used, with the transformers connected in such a manner as will give a fairly well-balanced three-phase load.

There are many arrangements and combinations of apparatus made possible by the use of alternating current in the car equipments, which have not been mentioned, as it is impracticable to give a full description of all that can be done. But enough has been presented to outline the apparatus and to indicate the possibilities of this new system which is soon to see the test of commercial service.

SYNCHRONOUS MOTORS FOR REGULATION OF POWER FACTOR AND LINE PRESSURE

FOREWORD—In 1890, the author discovered, during certain experiments in the Westinghouse testing room, that a synchronous motor could affect the power factor of the supply system, by variations in its field strength. Later, he proposed the use of such a machine for regulating the pressure of a supply system and for changing the relation between e.m.f. and current in alternating-current systems. However, even as late as 1904, when the paper was presented, the value of this method of operation was but little appreciated.

This paper should be read from the viewpoint of the time when it was written. Hand regulation was the ordinary practice. Consequently, alternators with inherently good regulation, that is, which would give three to four times full load current on sustained short circuit, were preferred, in order that much hand regulation would not be needed. This paper was presented at a meeting of the American Institute of Electrical Engineers in June, 1904.—(ED.)

IT is well known that the synchronous motor, running on an alternating-current circuit, can have its armature current varied by varying its field strength. A certain adjustment of field strength will give a minimum armature current. Either stronger or weaker fields will give increased current. These increased currents are to a great extent wattless. If the field is weaker than the normal (or field for minimum armature current), the increased armature current is leading with respect to the e.m.f. waves in the motor and lagging with respect to the line e.m.f. For stronger than the normal field, the current is to a great extent lagging and tends to lessen the flux in the motor and the current is leading with respect to the line e m f A synchronous motor therefore has an inherent tendency to correct conditions set up by improper adjustment of its field strength The correcting current in the motor being drawn from the supply system has a correcting effect on such system, tending to produce equalization between generated pressures in the motor and the supply pressure. This characteristic of the synchronous motor can readily be utilized for two purposes; namely, for varying the amount of leading or lagging current in a system for producing changes in the power-factor of the system (including transmission line, transformers, and generators), or a synchronous motor can be utilized for pressure regulation in a system.

As the synchronous motor can be made to impress a leading current upon the system, and as the amount of this leading current will depend upon the field adjustment of the synchronous motor, it is evident that this property can be used for neutralizing the effects of lagging current due to other apparatus on the system. The resultant leading or lagging current can be varied and the power-factor controlled over a fairly wide range depending upon the location of the synchronous motor or motors, and upon the current capacity of the motor, etc.

As the wattless current in the motor is primarily a corrective current, it is evident that for most effective purposes for adjusting power-factor on the system the corrective action of this current on the motor should not be too great. When used for such purpose the synchronous motor should therefore be one which would give a comparatively large current if short-circuited as a generator Also the motor should preferably be one in which the magnetic circuit is not highly saturated, for in the saturated machine the limits of adjustment in the field strength are rather narrow.

As has been noted above, if the field strength of the motor be varied, a leading or lagging current can be made to flow in its armature circuit, this current being one which tends to adjust the pressure of the armature and that of the supply system. It is evident that if the armature pressure is held constant and the supply pressure varied, a leading or lagging current would also flow. If for instance the line pressure were dropped below that of the motor, then a lagging current would flow in the motor tending to weaken its field, and a leading current would flow in the line, tending to raise the pressure on the line. If the line pressure should be higher than that of the synchronous motor, then the current in the motor would be leading, tending to raise its pressure; while it would be lagging with respect to the line, tending to lower its pressure. The resultant effect would be to equalize the pressures of the line and motor, and there would thus be a tendency to regulate the line pressure to a more nearly constant value. It is evident that the less the synchronous motor is affected by the corrective current and the more sensitive the line is to such corrective action, the greater the tendency will be toward constant pressure on the line It is therefore evident that the synchronous motor which gives the largest current on short circuit as a generator would be the one which gives the greatest corrective action as regards pressure regulation of the system.

For such regulation, the synchronous motor which gives a comparatively large leading or lagging current with small change to the pressure of the system is the most suitable one. Or, the motor which gives the greatest change in the leading or lagging current is the one which gives best regulation. It is the change in the amount of wattless current which produces the regulation. This current could vary from zero to 100 leading, for example, or could change from 50 leading to 50 lagging, or could change from 100 lagging to zero lagging. Any of these conditions could produce the desired regulating tendency, but all would not be equally good as regards the synchronous motor capacity. If in addition to the regulating tendency it is desired to correct for lower power-factor due to other apparatus on the circuit, it would probably be advisable to run a comparatively large leading current on the line due to the synchronous motor, and the regulating tendency would be in the variations in the amount of leading current, and not from leading to lagging, or *vice versa*. A larger synchronous motor for the same regulating range would be required than if the motor were used for pressure regulation alone. It is evident that the current capacity of a motor regulating from 50 leading to 50 lagging need be much less than for current regulating from 100 leading to zero. It is evident therefore that if there is to be compensation for power-factor as well as regulation of pressure, that additional normal current capacity is required.

In case such synchronous motors are required for regulation purely, it may be suggested that such machines be operated at very high speeds compared with ordinary practice. At first glance it would appear that such a synchronous motor could be operated at the highest speed that mechanical conditions would allow, but there are other conditions than mechanical ones which enter into this problem. For instance, it is now possible to build machines of relatively large capacity for two poles for 60-cycle circuits, and for very large capacities—say 1500 kilowatts—having four poles. Therefore mechanical conditions permit the high speeds, and the electrical conditions should be looked into carefully to see whether they are suitable for such service. As such synchronous motors should give relatively large currents on short circuit the effect of high speeds and a small number of poles on short-circuit current should be considered.

In order to give full-load current on short circuit, the field

ampere-turns of such a machine should be practically equal to the armature ampere-turns, taking the distribution of windings, etc., into account By armature turns in this case is not meant the ampere wires on the armature, but the magnetizing effect due to these wires Therefore to give, for instance, five or six times full-load current on short circuit, the field ampere-turns should be relatively high compared with the armature This means that the field ampere-turns per pole should be very high, or the armature ampere-turns per pole very low Experience shows that for very high speed machines, such as used for turbo-generators, there is considerable difficulty in finding room for a large number of field ampere-turns, and therefore in such machines it is necessary to reduce the armature ampere-turns very considerably for good inherent regulating characteristics This in turn means rather massive construction, as the magnetic circuit in both the armature and field must have comparatively large section and the inductions must be rather high. This in turn means high iron losses in a relatively small amount of material compared with an ordinary low-speed machine, and abnormal designs are required for ventilation, etc., and for mechanical strength

An increase in the number of poles usually allows increased number of field ampere-turns without a proportionate increase in the number of armature ampere-turns This condition is true until a large number of poles is obtained when the leakage between poles may become so high that the effective induction per pole is decreased so that there is no further gain by increasing the number of poles, unless the machine is made of abnormal dimensions as regards diameter, etc. Experience has indicated that in the case of very high-speed and very low-speed alternators, it is more difficult to obtain a large current on short circuit than with machines with an intermediate number of poles For example, it is rather difficult to make a 600 kilovolt-ampere, 3600-rev. per min., 2-pole machine which will give three times full-load current on short circuit A 4-pole, 1800 rev. per min. machine can more easily be made to give three times full-load current on short circuit and with comparatively small additional weight of material The material in the rotating part of the four-pole machine, while of greater weight, may be of considerably lower cost per pound. The stationary part of the four-pole machine may have a somewhat larger internal diameter, but the radial depth of sheet-steel will be less

than in a two-pole machine. The total weight of material in the armature of a four-pole machine may be practically no greater than in a two-pole machine. Therefore a two-pole machine of this capacity should cost more than a four-pole machine, if designed to give the same current on short circuit. A six-pole machine would show possibly a slight gain over the one with four poles, but not nearly as much as the four-pole machine would over the one with two poles The real gain of the six-pole over the four-pole construction would be in obtaining a machine which would give more than three times full-load current on short circuit. It would possibly be as easy to obtain four times full load current on short circuit with a six-pole machine as to obtain three times full load current on four-pole machine. An eight-pole machine would be in the same way somewhat better than the six-pole machine Therefore if a 600 kilovolt-ampere machine giving six times full-load current on short circuit is desired, it would be advantageous to make the machine with possibly eight to twelve poles. The question of which would be the cheaper would depend upon a number of features in design.

If very large short-circuit currents are desired, then, as indicated above, the number of poles for a given capacity should be increased, or the normal rating of the high-speed machine should be decreased. If, for example, the 600 kilovolt-ampere, 3600 rev. per min. machine, mentioned above, should be rated at 200 kilovolt-amperes, then it could give nine times full-load current on short circuit; but such a method of rating is merely dodging the question.

In general, the following approximate *limits* for speeds and short circuit currents for 40-cycle apparatus can be given. These limits are necessarily arbitrary, and are intended to represent machines which could probably be made without using too abnormal dimensions,

600 kilovolt-amperes, 3600 rev. per min., two to three times full-load current on short circuit.

1000 kilovolt-amperes, 1800 rev. per min., three to four times full-load current on short circuit.

1500 kilovolt-amperes, 1200 rev. per min., four to five times full-load current on short circuit.

2500 kilovolt-amperes, 900 rev. per min , four to five times full-load current on short circuit.

For 25 cycles it is more difficult to give limiting conditions,

as the choice of speeds is very narrow. If, for example, a 1500 kilovolt-ampere, 2-pole, 1500 rev per min. machine can be made to give three times full-load current on short circuit, then as machines of smaller rating cannot run at higher speed, the limiting condition of such machines must be the amount of current which they will give on short circuit In the same way a 4-pole machine running at 750 rev per min. may be made for 5000 kilovolt-amperes for three times full-load current as the limiting rating, and there is no choice of speeds for ratings between 1500 kilovolt-amperes and 5000 kilovolt-amperes.

It should be noted that the above speeds are very high compared with ordinary alternator practice and are up to high-speed turbo-generator practice, but machines with the above short-circuit ratings and speeds are probably more costly to build than machines of corresponding ratings at somewhat lower speeds It will probably be found therefore that for the above maximum current on short circuit the cheapest synchronous motors for the given ratings will have somewhat lower speeds than those indicated above It is certain that the lower-speed machines will be easier to design and will be slightly quieter in operation Probably best all-round conditions will be found at about half the above speeds.

The above limiting conditions are given as only approximate and are based upon machines having ventiliation as is usually found on rotating field generators for high speed. Artificial cooling, such as obtained with an air-blast or blowers could modify the above figures somewhat; but in general it has been found that high-speed alternators can be worked up to the limit imposed by saturation before the limit imposed by temperature is attained. Therefore if higher saturation is not permissible, then there may be relatively small gain by using artificial cooling.

One of the principal applications of such regulating synchronous motors would be for controlling or regulating the pressure at the end of a long transmission line for maintaining constant pressure at the end of the line, independent of fluctuations of load or change of power-factor. In this case, increased output of the transmission line may more than compensate for the cost of the regulating synchronous motor. In such a case the synchronous motor not only acts as a regulator on the system but costs nothing in the end. In general, the more current that such a synchronous motor will give on short-

circuit, the better suited it will be for its purpose at the end of a long transmission line

Where a number of such synchronous motors are installed in the same station, the field adjustment must be rather carefully made, to avoid cross-currents between machines, and the saturation characteristics of the various machines should be very similar. The better such machines are for regulating purposes, the poorer they are for equalizing each other by means of cross-currents

As to the use of dampers with such synchronous motors, it is difficult to say just what is required A synchronous motor on a line with considerable ohmic drop is liable to hunt to some extent, especially if the prime mover driving the generator has periodic variations in speed If the synchronous motor gives very large current on short circuit, then its synchronizing power is high, this will tend to steady the operation of the motor and decrease the hunting. The writer believes that such motors in practice will be found to operate better and have better regulating power for constant pressure if provided with rather heavy copper dampers effectively placed on the field poles. With such heavy dampers reaction of the armature on the field is retarded, and therefore the armature may give a larger momentary current than would flow it there were no damping effect; in other words, the motor is more sluggish than one without dampers Therefore the addition of heavy dampers on such a machine may produce the same regulating effect which would be obtained by a machine without dampers which gives a larger current on short circuit. Also a machine with heavy dampers will usually be the one with the least hunting tendency and therefore will have the least effect on the transmission line due to hunting currents.

In the above, the synchronous motor has been considered only as a regulator and not as a motor. It may be worth considering what would be the effect if the synchronous motor can do useful work at the same time that it regulates the system. In this case, with a given rated output, one component of the input will be wattless, and the other part will be energy. The ratio of these two components could be varied as desired. For example, considering the input as 100, the wattless component could be 60 when the energy component is 80; or the synchronous motor could carry a load of 80% of its rated capacity, this load including its own losses, and could

have a regulating component of 60% of its rated capacity. If the motor is used as a regulating machine only, then its wattless component can be practically 100 It appears therefore that the machine could be used more economically as both motor and regulator than as a regulator alone, but in such case it would probably be advisable to run the motor at somewhat lower speed than if operated entirely as a regulator. This reduction in speed may practically offset the gain in apparent capacity by using the machine for a double purpose. Also there is comparatively limited use for large synchronous motors for power purposes, as better results are usually obtained by subdividing the units and locating each unit nearest to its load. If a load could be provided which would permit very high-speed driving, then it would probably be of advantage to utilize the synchronous motor for driving

As the synchronous converter is one form of synchronous motor, the question of utilizing such machines for regulators should be mentioned. Upon looking into the question of distribution of losses in the converter, it will be noted that the losses in the armature winding are not uniform Investigations show that at 100% power-factor, the lowest heating in copper is obtained, and that any departure from this power-factor shows considerably increased loss in the copper, such loss being very high in certain portions of the winding Next to the taps which lead to the collector there are strips of winding which at times are worked at a very high loss. Experience shows that it is not advantageous to operate converters at a low power-factor, and that if so operated continuously, or for any considerable periods, the winding should be made much heavier than for higher power-factors. Also in the usual design of converters the field is not made as strong compared with the armature as in alternator practice, and therefore the regulating tendency of the converter compared with a generator or ordinary synchronous motor, is low. Synchronous converters can and do act as regulators of pressure for sudden changes of the supply pressure, but such correcting or regulating action should not be continual; that is, the pressure supplied to a converter from a line should nominally be that required by the converter for best operation as a synchronous converter. Unless designed for the purpose, a synchronous converter should not be used to correct low power-factors due to other apparatus on the circuit.

In the above considerations only general reference has been made to the cost of synchronous motors for regulating pressure and power-factors It is difficult to give even approximate figures for relative costs of such apparatus As intimated before, there is some mean speed or number of poles which will be the most suitable for giving a certain maximum current on short circuit. For speeds slightly above or below such mean speed, the cost of the synchronous motor should vary almost in proportion to the speed, provided the maximum short-circuit current can be diminished somewhat at the same time If the speed is further increased or further decreased, the cost will tend to approach a constant figure As the extreme conditions are approached, the cost will begin to rise. The above assumptions are on the basis of continuous operation at a given current capacity, this being the same in all cases. The above assumption is on the basis of decrease in the maximum short-circuit current, as the machine departs from the mean, or best speed. If the same maximum current is required, then the lowest cost should be at the mean or best speed, while at either side the cost should rise.

It is evident that it would be difficult to give any figures on relative costs of such apparatus. The machine for the best or mean condition, should cost practically the same as an alternating-current generator of the same speed, output, and short-circuit characteristics. As this speed would probably be somewhat higher than usual generator speeds, the cost of such machine would therefore be somewhat lower. This cost would be to a considerable extent, a function of the current on short circuit for a given rated capacity of machine. As mentioned before, in giving a table of limiting speeds and short circuits, it is probable that one-half this limiting speed would be near the best condition. Such machines would probably cost from 60% to 80% as much as similar machines for usual commercial high-speed conditions. neglecting turbo-generator practice. The frequency has considerable effect on this, as, for example, there is small choice of speed as regards high-speed 25-cycle machines. Taking very general figures only, it is probable that in the case of a given capacity of machine for say three or four times full-load current on short circuit the cost cannot be expected to be lower than one-half that of machines of similar rating at ordinary commercial speeds, turbo-generator practice being excluded. The costs in general should approximate more nearly

those of turbo-generators, but again, an exact comparison cannot be made because in usual practice the turbo-generators do not give three to four times full-load current on short circuit.

There are a number of other conditions in this general problem, such as advantage or disadvantage of placing synchronous motors in the main power-house, or distributing them in a number of sub-stations Also there is the question of the effect of the cost on the generating plant when used with such regulating synchronous motors. If higher power-factors are maintained on the transmission system and generator, a cheaper form of generator can probably be used. The high power-factor permits a larger output from the transmission system and thus represents a gain. If the synchronous motor can be operated at its best speed and also do work, then there is a further gain If the synchronous motor should be located at the center of power distribution, and the power is distributed through induction motors, then there is a possibility of reducing the cost of such motors by lowering the power-factor, this being compensated for by the synchronous motor delivering leading currents As the cost per horse power of small motors will be much greater than the cost per horse power of a large regulating motor, there is a possibility of gain from this source. If the induction motors are distributed over wide territory, this gain would be lessened and might disappear.

It should be mentioned that the power-factor of a system as influenced by difference in wave form has not been considered in the preceding discussion. It is obviously impossible to neutralize by a synchronous motor the effect of currents in a system due to difference in wave form. Such currents will in general be of higher frequency than the fundamental wave of the system, and the synchronous motor obviously could not correct for them, unless it impressed upon the system opposite waves of the same frequency. This would mean a synchronous motor with a different wave form from that of the system.

The power-factor of a system will also be affected by any hunting of the apparatus on the system. It is evident that the synchronous motor could not correct or neutralize such effects, except through exerting a damping effect on the system and other apparatus on the system. A synchronous motor with heavy dampers can reduce the hunting in a system, but such hunting can also be damped by induction motors with low-resistance secondaries, especially if of the cage type. This

correcting effect should therefore be credited to the damper rather than to synchronous-motor action. There are a number of other questions which arise in connection with this regulating feature of the synchronous motor, but the subject is too broad to permit even mention of them.

The substance of the preceding statements can be summarized as follows:

1. A synchronous motor can be used to establish leading or lagging currents in its supply system by suitable field adjustment, and can thus affect or control power-factor or phase relations of the current in the alternating current system

2. A synchronous motor will set up leading or lagging currents in its supply system if its field strength is held constant, and the pressure of the supply system is varied above or below that generated by the synchronous motor Such leading or lagging currents in the supply system will tend to vary the pressure of the system A synchronous motor can thus act as a regulator of the pressure of its supply system.

3. This regulating action is greatest with synchronous motors which have the closest true inherent regulation (as indicated by high field magnetomotive force compared with the armature magnetomotive force) in distinction from machines which have close apparent regulation obtained by saturation of the magnetic circuit.

4. If the synchronous motor is used both for regulating the power-factor for neutralizing the effect of other apparatus on the circuit, and for regulating or steadying the pressure of the supply system, its normal capacity for regulating will be diminished.

5. The most suitable speeds for best electrical conditions will in general be considerably below highest possible speeds as limited by mechanical conditions.

6. Heavy dampers will increase the effectiveness of the regulating tendency.

7. If the synchronous motor can be used for power purposes as well as for regulation, its apparent capacity is increased. This is due to the fact that the regulation is obtained by means of a wattless component and the power from the energy component, and the algebraic sum of these two is greater than their resultant which fixes the current capacity of the machine.

8. Synchronous converters in general are not suited for regulating the pressure or controlling the power-factor of an alternating-current system.

9. The costs of synchronous motors for regulating purposes will in general be lower than for alternating-current motors or generators of customary speeds, and will approach more nearly to turbo-generator practice

DATA AND TESTS ON 10 000 CYCLE PER SECOND ALTERNATOR

FOREWORD—In 1902, the author undertook the construction of 10 000 cycle per second alternator. This problem was a very new and radical one at that time and it was considered worth while to put the record of results in permanent form. Therefore, this paper was prepared on the subject and presented before the American Institute of Electrical Engineers in May, 1904. This is interesting merely as a record of a relatively early construction.—(ED)

IN the early part of 1902, M. Leblanc, the eminent French engineer, was in this country, and spent considerable time at the Westinghouse Electric & Manufacturing Company's works at East Pittsburg. M. Leblanc was very much interested in certain special telephone work, and in connection with such work he desired for experimentation a current of very high frequency. He took up with the writer the question of building a successful alternator for generating current at frequencies between 5000 and 10 000 cycles per second. He was informed that the machine would necessarily be of very special construction, but that it was not an impossible machine. Later he took up the matter with Mr. Westinghouse, who, upon receiving satisfactory assurance that such a machine was possible, advised that the generator be built. A preliminary description of the general design was given M. Leblanc before he returned to Paris. He was somewhat surprised at certain of the features proposed, especially at the fact that an iron-cored armature was considered feasible for a frequency of 10 000 cycles per second.

The machine was designed and built on practically the lines of the preliminary description furnished M. Leblanc. The frequency being so abnormal, the writer believes that many features in the machine, with the results obtained, will be of scientific interest, and therefore the data of the machine, and the tests obtained are presented herewith

The starting point in this machine was the sheet-steel to be used in the armature. No direct data were at hand showing losses in sheet-steel at such high frequencies, nor was there at

hand any suitable apparatus for determining such losses. As preliminary data, tests at frequencies up to about 140 cycles per second were used and results plotted in the form of curves; these results were plotted for different thicknesses of sheet-steel. Also, tests were obtained showing the relative losses due to eddy currents and hysteresis, and these were plotted, taking into account the thickness of the sheets. These data were not consistent throughout; but the general shape of the curves was indicated, and in this way the probable loss at the frequency of 10 000 cycles per second was estimated for the thinnest sheet-steel which could be obtained. The steel finally obtained for this machine was in the form of a ribbon about 2 in. wide, and about 0.003 in. thick, which was very much thinner than any steel used in commercial dynamos or transformers, which

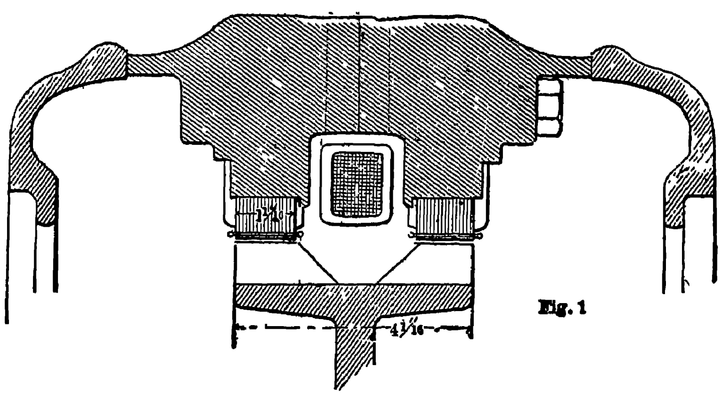


Fig. 1

varies from 0.125 to 0.0280 inch. Therefore the machine had to be designed with the intention of using this narrow ribbon of steel for the armature segments.

A second consideration of great importance in the construction of such a machine is the number of poles permissible for good mechanical construction. For instance, at 3000 revolutions—which was adopted as normal speed—the number of poles required is 400 for 10 000 cycles per second. The frequency, expressed in terms of alternations per minute, multiplied by the pole-pitch in inches, gives the peripheral speed in inches. At 1 200 000 alternations per minute (or 10 000 cycles per second) and a pole pitch of 0.25 in., for example, the peripheral speed of the field will be 25 000 feet per minute. It was therefore evident that either a pole construction should be

adopted which would stand this high peripheral speed, or the pole-pitch should be less than 0.25 in. It was finally decided that an inductor type of alternator would be the most convenient construction for this high frequency; with the inductor type alternate poles could be omitted, thus allowing 200 pole projections, instead of 400. The field winding could also be made stationary instead of rotating, which is important for such a high speed. This construction required a somewhat larger machine for a given output than if the usual rotating type of machine were adopted; but in a machine of this type where everything was special, the weight of material was of comparatively little importance, and no attempts were made to cut the weight or cost of the machine down to the lowest possible limits.

The following covers a general description of the electrical and magnetic features of the machine.

Armature.—The armature was built up in two laminated rings dovetailed into a cast-iron yoke, as indicated in Fig. 1.

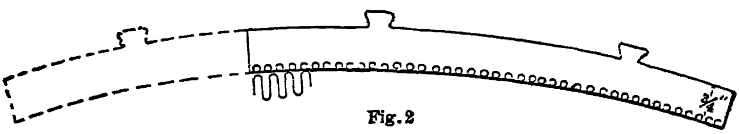


Fig. 2

The laminations were made in the form of segments dovetailed to the cast-iron yoke (Fig. 2). Special care was taken that the laminations made good contact with the cast-iron yoke, as the magnetic circuit is completed through the yoke.

The armature sheet-steel consisted of plates of 0.003 in. thickness. The sheet-steel was not annealed after being received from the manufacturer; it was so thin that to attempt annealing was considered inadvisable. To avoid eddy currents between plates each segment was coated with a thin paint of good insulating quality. This painting was a feature requiring considerable care and investigation, as it was necessary to obtain a paint or varnish which was very thin, and which would adhere properly to the unannealed laminations. These laminations had a bright polished appearance quite different from that of ordinary steel. They were so thin that the ordinary paint or varnish used on sheet-steel made a relatively thick coating, possibly almost as thick as the plates themselves. A very thin varnish was finally obtained which gave a much thinner coating than the plate itself, so that a relatively small part of the armature space was taken up by the insulation between plates.

Each armature ring or crown has 400 slots. Each slot is circular and 0 0625 inch diameter (Fig 3) There is 0.03125 inch opening at the top of the slot into the air-gap, and the thickness of the overhanging tip at the thinnest point is 0 03125 inch

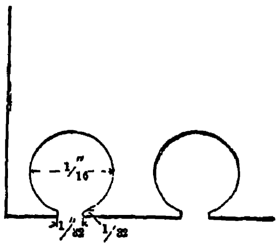


Fig. 3

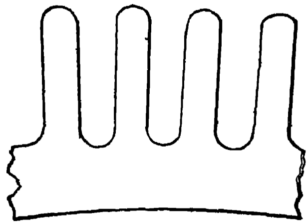


Fig. 5

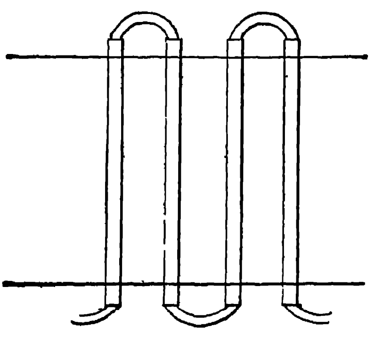
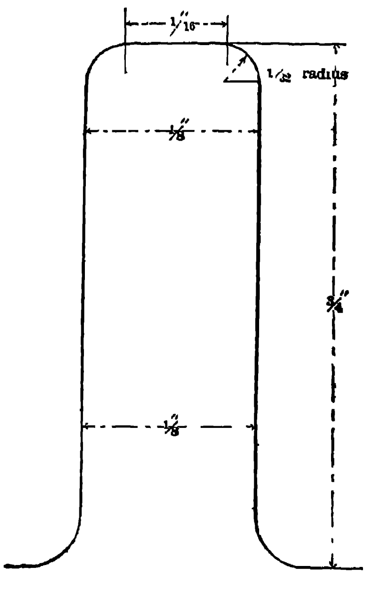


Fig. 4



The armature winding consists of No 22 wire, B. & S gauge, and there is one wire per slot. The entire winding is connected in series (Fig 4) The measured resistance of the winding is 1.84 ohms at 25° cent.

After the sheet-steel was built up in the frame, it was ground out carefully. The laminations were then removed, all burred edges taken off and the laminations again built up in the frame. The object of this was to remove all chances of eddy currents

between the plates due to any filing or grinding. The finished bore of the armature is 25.0625 inch.

Field or Inductor. — This was made of a forged-steel disc 25 in. diameter turned into the proper shape, and the poles were formed on the outside by slotting the periphery of the ring. The general construction is indicated in Figs. 1 and 5. The poles were 0 125 in wide and about 0 75 in. long radially and were round at the pole-face. Fig. 6 shows the general dimensions of a pole.

The field winding consisted of No 21 wire, B. & S. gauge. There were 600 turns total arranged in 30 layers of 20 turns per layer. The field coil after being wound was attached to a light brass supporting ring. The general arrangement of the field or inductor, armature yoke, and bearings, is as indicated in Fig 1. The measured resistance of the field winding is 53 8 ohms at 25° cent.

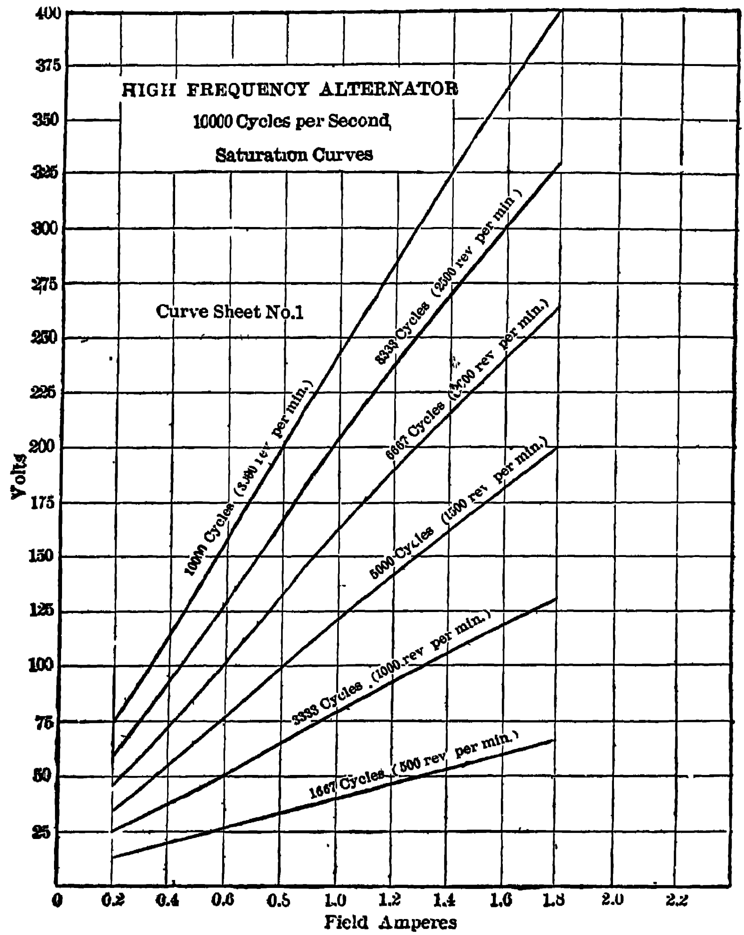
Tests.—The machine was designed primarily for only a small output, but was operated on temporary test up to 2 kw. A series of curves were taken at 500, 1000, 1500, 2000, 2500, and 3000 revolutions, giving frequencies from 1667 to 10 000 per second. At each of the above speeds, saturation curves, iron losses, and short-circuit tests were made. Friction and windage were also measured at each speed.

On account of the high frequency, the machine was worked at a very low induction; consequently there is an extremely wide range in pressure, the normal operating pressure being taken at approximately 150 volts.

On curve sheet No. 1, the saturation curves for the various speeds are given. These curves check fairly well, the pressure being practically proportional to the speed with a given field charge. This is to be expected at the lower speeds, but it was considered possible that at 3000 revolutions the air-gap might be slightly lessened, due to the expansion of the rotor under centrifugal action; and it was also thought that eddy-current loss due to the high frequency might affect the distribution of magnetism at the armature face, but the armature iron losses were comparatively small, and there appeared to be no such effect. Also there appears to be no effect due to expansion at high speed. The air-gap specified for this machine is 0 03125 in. on each side or 0.0625 in total gap. A very small variation in the diameter of the inductor or the bore of the armature

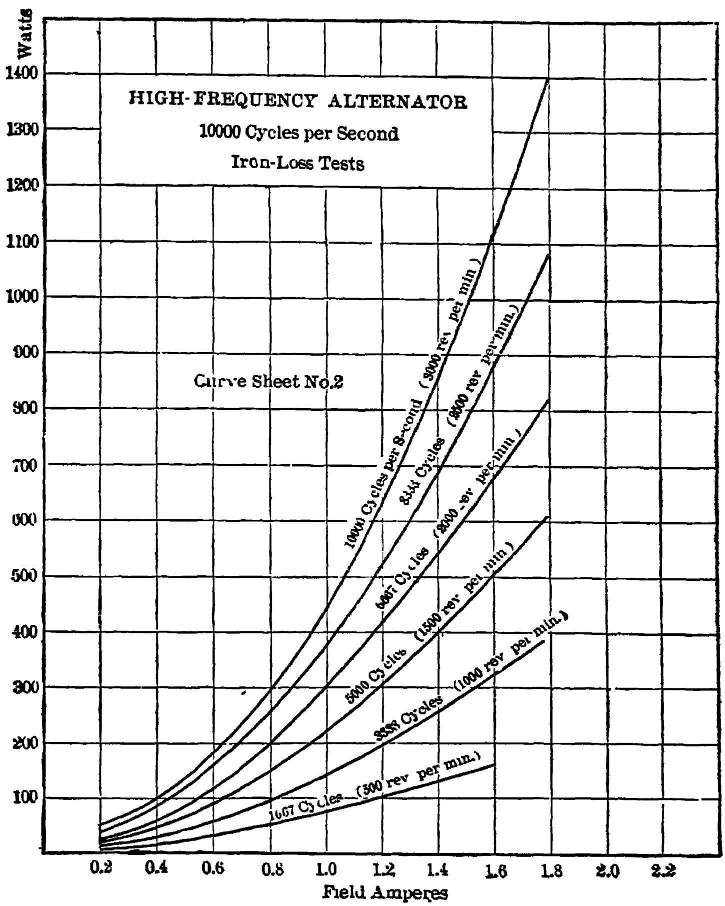
would make a relatively large per cent. in the effective air-gap. Therefore no reliable calculations can be made on the saturation curves of this machine based upon the specified air-gap.

Curve sheet No. 2 shows the iron losses at various speeds from 500 to 3000 rev. per min.—1667 to 10 000 cycles per second. These losses are plotted in terms of watts for a given exciting



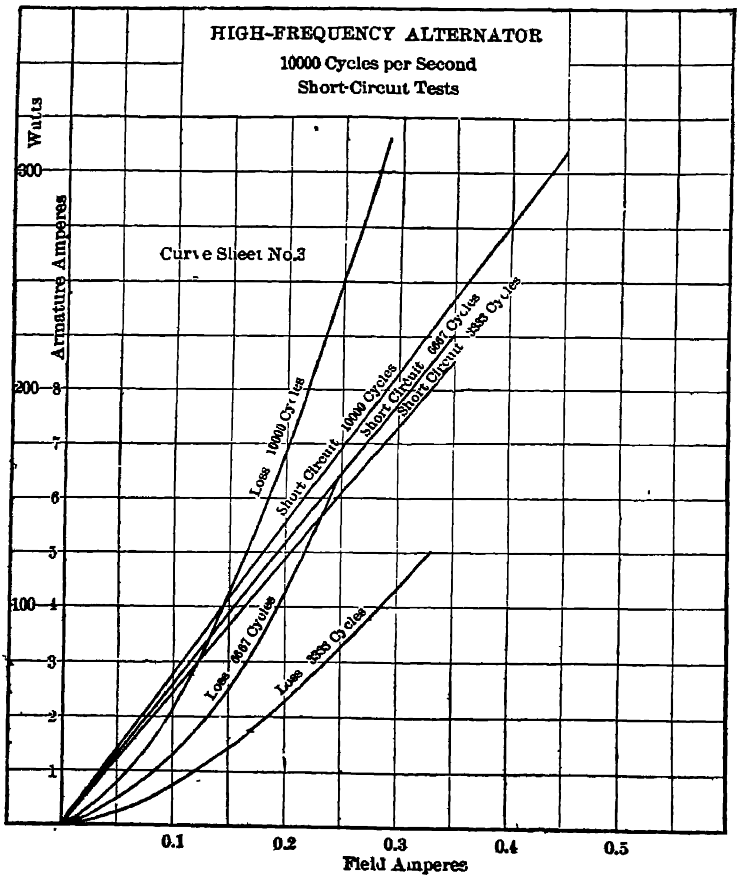
current. These curves show a rather unexpected condition as regards the losses. According to the original data showing the relative losses due to eddy currents and hysteresis, the eddy-current loss even with these thin plates should have been much higher than the hysteresis loss, but these iron-loss curves show

losses with a given field charge almost proportional to the frequency, which is the ratio that the hysteresis loss alone should show. As the eddy-current loss varies as the square of the frequency, the writer expected this to be a large element in the total iron loss, especially at the higher inductions. The six curves shown on this test-sheet are fairly consistent



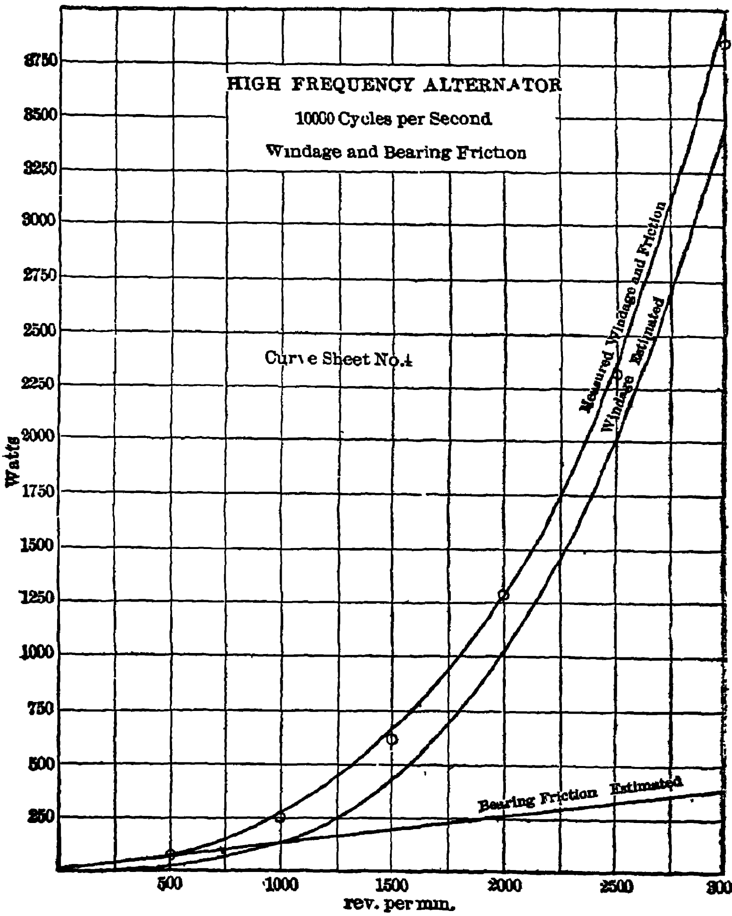
with each other, but it should be remembered that in making measurements of such abnormal apparatus little discrepancies in the curves could easily creep in. For instance, in the saturation curve a series of experiments were first made to find whether usual types of voltmeters were satisfactory, and a num-

ber of different methods for checking these readings were used. In determining the iron losses in curve sheet No. 2, the machine was driven by a small motor and the losses measured with different field charges. Under most conditions of test the iron loss was a small element of the total loss, and therefore slight variations in the friction loss would apparently show large variations



in the iron losses. Also the fly-wheel capacity of the rotating part of the alternator was comparatively high. Therefore, if there are any variations in the circuits supplying the driving motor, there would tend to be considerable fluctuations in the power supplied. Considering all the conditions of test, the curves appear to be remarkably consistent.

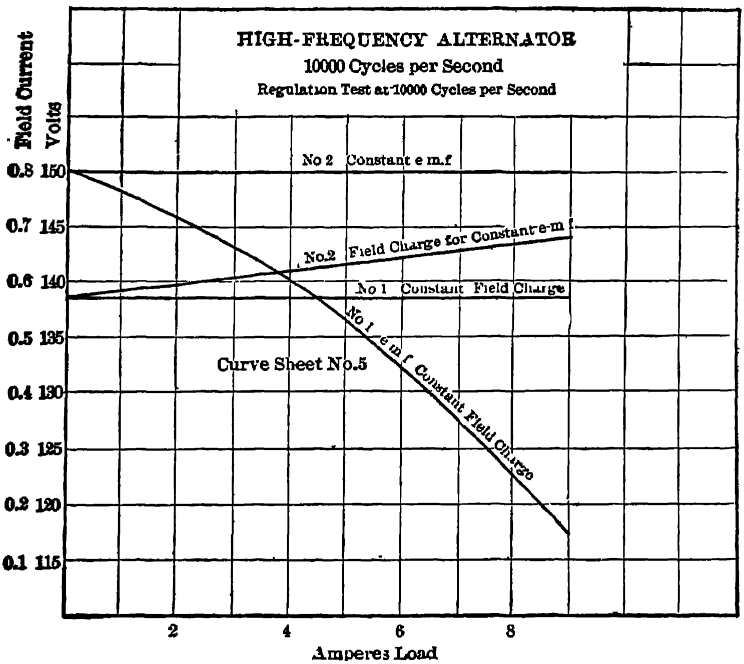
Curve sheet No. 3 shows the short-circuit curves at speeds of 1000, 2000, and 3000 rev. per min., or frequencies of 3333, 6667, and 10 000 cycles per second, respectively. It should be noted that at a given frequency the short-circuit current is proportional to the field current over the entire range measured



but that the short-circuit current is not the same for the same field current at the various frequencies. According to these curves the current on short circuit increases somewhat with the given field charge as the frequency is increased.

Curve sheet No. 4 shows the measured windage and friction losses plotted at speeds from 500 to 3000 rev. per min. This

curve indicates clearly that the windage is the principal friction loss at the higher speeds. The writer has added two curves, one showing the estimated bearing friction loss, and the other the estimated windage, based upon the assumption that the bearing friction varies directly as the revolutions and the windage loss with the third power of the revolutions. The small circles lying close to the measured loss curve show the sum of these estimated losses, and the agreement with the measured loss is fairly close over the entire range.



Curve sheet No. 5 shows regulation tests made at 150 volts. The power-factor of the load on this test was not determined, and it was extremely difficult to make accurate measurements. The load consisted of incandescent lamps and the wiring from the machine to the lamps was non-inductive for the usual frequencies; but at the abnormal frequency of 10 000 cycles per second it is more difficult to obtain a true non-inductive load with ordinary apparatus. The tested regulation indicates that the load was practically non-inductive.

In first undertaking tests on this machine there was consid-

erable difficulty in measuring the pressures. It was found that at a frequency of 10 000 cycles per second the Weston voltmeter did not work satisfactorily. Practically the same deflection was obtained on the high and low scales of a 60-120 volt Weston alternating-current direct-current voltmeter with the same pressure.

Very good results were obtained by the use of a form of static voltmeter devised by Mr. Miles Walker. This voltmeter is of the same form as the static wattmeter described by Mr. Walker before the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, May 1902.* Tests were also made with the Cardew hot-wire voltmeter with the high frequencies, and the results checked very satisfactorily with the static voltmeter.

For measuring the current a current dynamometer was used which had wood upright supports and a celluloid dial. The only metal parts outside of the copper coils were brass screws. It was found that the current dynamometer is not affected by frequency, unless there are adjacent metal parts in which eddy currents can be generated which react upon the moving element. The dynamometer used had but a few turns in order to reduce the pressure drop across it. This dynamometer was checked very carefully at different frequencies and apparently gave similar results for any frequency between 25 and 10 000 cycles.

Several temperature tests were made on this machine. The heaviest load on any test was 13.3 amperes at 150 volts, or 2-kw. output. This test was of two hours' duration, and at the end the armature iron showed a rise of 16° cent.; the armature copper 21° cent. by resistance, and the field copper 17.3° cent. Air temperature 19° cent. The machine showed a relatively small increase in temperature at this load over the temperature rise with one-third this load. This was probably due to the fact that the windage loss was so much higher than the other losses of the machine that the temperature was but little affected by the small additional loss with increase in load.

Attempts were made to utilize the current from this machine for various experiments, but difficulty was at once found in transforming it. At this high frequency no suitable iron-cored transformer was available. Transformers with open magnetic circuits were tried and operated better than those with iron cores but were still rather unsatisfactory. It was decided that nothing could be done in this line without building special transformers.

[*TRANSACTIONS of the A. I. E. E., Vol. XIX. p. 1035.]

Among the few experiments made was that of forming an arc with current at this high frequency. This arc appeared to be like an ordinary arc so far as the light was concerned, but had a very high-pitched note corresponding to the high frequency. This note was very distressing to the ears.

This machine is in reality of the nature of a piece of laboratory apparatús; and at present it has no commercial value. It was designed primarily for scientific investigation, and appears to be a very good machine for that purpose.

THE SINGLE-PHASE COMMUTATOR TYPE RAILWAY MOTOR

FOREWORD—This paper was presented before the Philadelphia Section of the American Institute of Electrical Engineers in February, 1908. It describes, as simply as possible, the general construction and characteristics of compensated series single-phase motors —(ED.)

THE broad statement may be made that it is no more difficult to commutate an alternating current than an equal direct current Such a statement would appear to be entirely contrary to the usual experience, but a little study of the matter will show where the apparent discrepancy lies. In commutator type alternating-current motors, as usually built, a relatively large number of commutator bars pass off under the brush during one alternation of the supply current. While the current supplied is varying from zero to maximum value and back to zero, possibly 50 bars have been passed under the brush, and therefore 50 coils in the armature have been reversed or commutated. Some of these reversals occur at the top of the current wave which has a value of about 40% higher than the mean or effective value which is read by the ammeter. The motor is therefore at times commutating 40% higher current than that indicated by the instruments. It is thus evident that in comparing the commutation of 100 amperes direct-current with 100 amperes alternating-current we should actually compare the direct-current with 141 amperes alternating. In other words, for commutating equal currents alternating-current or direct-current, the alternating-current ammeter should register only 71% as much current as the direct-current. Another way of expressing it is that we have to commutate the top or maximum of the alternating-current wave, while our instruments only record the mean value.

If the above represented the only difference between the alternating current and direct current the problem to be solved in commutation of alternating current would not be serious.

However, the current to be commutated by an alternating-current motor is not merely the working current supplied to the motor and measured by the ammeter, but there is, in addition, a current which is generated in the motor itself, both at standstill and during rotation, which has to be reversed or commutated along with the working current. It is this latter current, usually called the local or short-circuit current, which has been the source of greatest trouble in commutating alternating current; for this short-circuit current may have a value anywhere from three to ten times the working current, depending on the design of the machine. Therefore in comparing the commutation of an alternating current, as indicated by an ammeter,

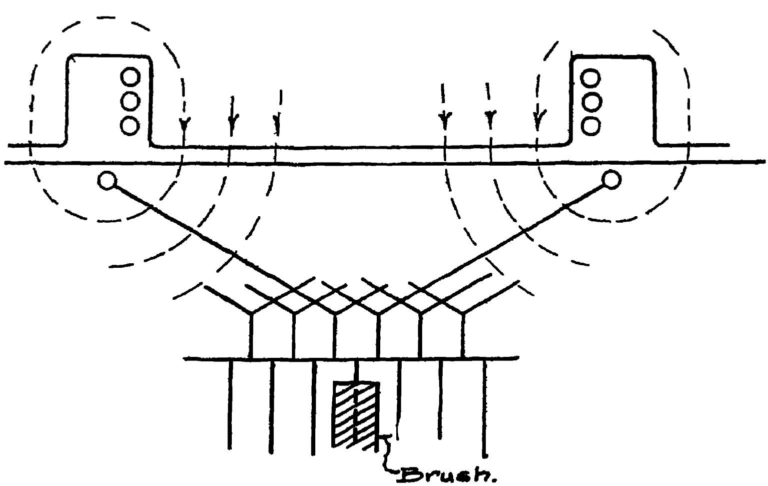


FIG. 1

with an equal direct current, we should, in reality, consider that the alternating-current motor is commutating a maximum current from five to ten times the value of the indicated current Furthermore, it would not do to reduce the ammeter current to one-fifth or one-tenth value in order to compare commutation with direct current, because by so doing we would simply be reducing the small applied component of the total current commutated by the brushes, the local or short-circuit current still retaining a rather high value. In order to compare with direct-current commutation, it would be necessary for the total maximum of the combined supply and the short-circuit current to be reduced to the same value as direct current.

It is the local current in the armature turn short-circuited by the brush which is the source of practically all the trouble in commutating alternating currents Fig 1 illustrates a portion of the field and armature structure of a commutator type alternating-current motor. It will be noted that the armature conductor, which is in the neutral position between poles, surrounds the magnetic flux from the field pole, just as the field turns themselves surround it. The field flux being alternating, this armature turn will have set up in it an electromotive force of the same value as one of the field turns. Short-circuiting the two ends of this armature turn should have the same effect as short-circuiting one of the field turns, which is the same thing as short-circuiting a turn on a transformer. Such a short-circuited turn, if of sufficiently low resistance, should have as many ampere-turns set up in it as there are field ampere-turns In single-phase motors of good design the field ampere-turns per pole are about twelve to fifteen times the normal ampere-turns in any one armature coil. Therefore, if the armature coil in the position shown in this Fig. 1 should have its ends closed on themselves the current in this coil would rise to a value of twelve to fifteen times normal In reality, it would not rise quite this much, because this armature turn is placed on a separate core from the field or magnetizing turns with an air-gap between, so that the magnetic leakage between the primary (or field winding) and this armature (or secondary winding) would tend to protect this coil somewhat, just as leakage between the primary and secondary windings of a transformer tends to reduce the secondary electromotive force and current. Also, this armature coil is embedded in slots, thus adding somewhat to its self-induction, and tending further to reduce the short-circuit current. In consequence, with its ends closed together the current in this armature coil would probably not rise more than ten to twelve times above normal value under any condition. It is evident, therefore, that if the brush shown in Fig. 1 as bridging across two commutator bars to which the ends of this coil are connected is of copper or other low-resistance material, then there could be an enormous local current set up in the coil when thus short-circuited by the brush. This local current of about ten times the normal working current would have to be commutated as the brush moves from bar to bar, and therefore the operation of the machine would be similar to that of a direct-current motor if overloaded about ten times in current. In other words, there would be vicious sparking.

Even if the low-resistance brush were replaced by one of ordinary carbon, the short-circuiting current would still be relatively high, due to the fact that it is not possible to make the brush contact of very high resistance by reducing the size or number of the brushes, because these same brushes must carry the working current supplied to the motor, and there must be brush capacity sufficient to handle this current. This brush capacity will, in practice, be of such amount that the resistance in bridging from one bar to the next is still rather low, although much higher than if a copper brush were used. Experience shows that with not more than four or five volts generated in this short-circuited coil by the field flux, the resistance of the carbons at the contact with the commutator would be such that a short-circuit current of three to four times the normal working current in the coil can still flow. Therefore, if the motor were equipped with carbon brushes and had but four or five volts generated in the short-circuit coil, the motor would have to commutate the main or working current and also a short-circuit current of possibly three times the amount. This short-circuit current would also have a maximum or top of its current wave. Assuming 100 amperes as the current supplied to the motor, the machine therefore actually commutates a supply current of 141 amperes and an additional short-circuit current of possibly three times this value, or from 400 to 500 amperes; therefore, the motor actually commutates the equivalent of about 600 amperes direct current when the alternating-current ammeter is reading 100. It is evident from this that any one who tries to commutate alternating current with an ordinary type of commutating machine would at once draw the conclusion that alternating current in itself is very difficult to commutate, naturally overlooking the fact that it is the excessive current handled by the brush that is back of the trouble, and not the current indicated by the ammeter.

From what has been stated, it is evident that the excessive local current is back of the difficulty in commutating alternating current. All efforts of designers of alternating-current commutator motors have been in the direction of reducing or eliminating this local current. The present success of the motor, in the various forms brought out, is largely due to the fact that this current has been successfully reduced to so low a value that it does not materially add to the difficulties of commutating the main current. No successful method has yet been practically

developed for entirely overcoming the effects of this short-circuit current under all conditions from standstill to highest speed. Some of the corrective methods developed almost eliminate this current at a certain speed or speeds, but have little or no corrective effect under other conditions; other methods do not effect a complete correction at any speed, but have a relatively good effect at all speeds and under all conditions. The former methods would appear to be applicable to motors which run at, or near, a certain speed for a large part of the time; the latter method would be more applicable to those cases where the motor is liable to be operated for considerable periods with practically any speed from standstill to the highest. While several methods have been brought forward for correcting local current when the motor has obtained speed, yet up to the present time but one successful method has been developed for materially reducing this current at standstill or very low speeds. It may be suggested that the short-circuit voltage per coil be reduced to so low a value, say four or five volts, that the local current is not excessive and does not produce undue sparking. This would certainly reduce the sparking difficulty, but is open to the very great objection that the capacity of the motor is directly affected by a reduction in the short-circuit voltage. This voltage per turn in the armature coil is a direct function of the value of the alternating field-flux and its frequency. Assuming a given frequency, then the short-circuit voltage is a direct function of the induction per field pole, and the lower the short-circuit voltage the lower must be the field flux. But the output of the machine, or the torque with a given speed, is proportional to the product of the field flux per pole by the armature ampere-turns. In a given size of armature the maximum permissible number of ampere-turns is pretty well fixed by mechanical and heating considerations, and therefore with a given armature the torque of the motor is a direct function of the field flux. Using the maximum permissible armature ampere-turns, the output of a given motor would be very low if the field flux were so low that the short-circuit voltage would not be more than three or four volts. Increasing the field induction, and therefore increasing the short-circuit voltage, increases the output.

Experience shows that on large motors, such as required for railway work, the induction per pole must necessarily be so high that the electromotive force in the short-circuit coil must be about double the figure just given; therefore, with such heavy

flux the short-circuited current will necessarily be excessive unless some corrective means is used for reducing it.

I will consider the standstill or low-speed conditions first For this condition only one practical arrangement has so far been suggested for reducing the local current to a reasonably low value compared with the working current. This method involves the use of preventive leads, or, as they are sometimes called, resistance leads These consist of resistances connected between the commutator bars and the armature conductors. Fig. 2 illustrates the arrangement. The armature is wound like a direct-current machine, except that the end of one armature coil is connected directly to the beginning of the next

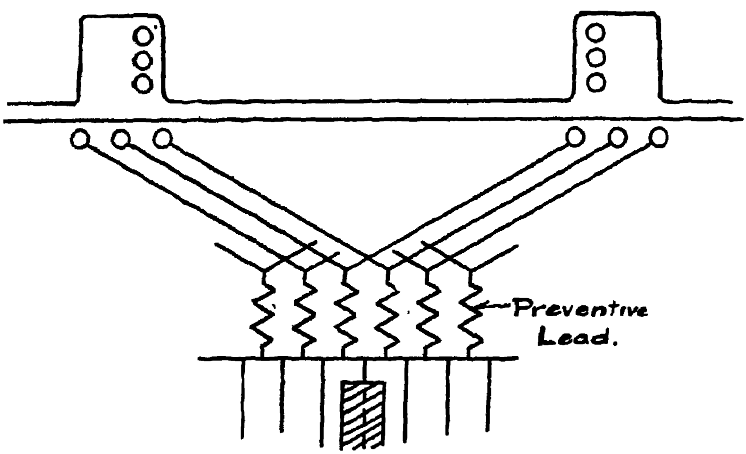


Fig 2

without being placed in the commutator Between these connections separate leads are carried to the commutator bars, and in these leads sufficient resistance is placed to cut down the short-circuit current. The arrangement is very similar in effect to the preventive coils used in connection with step-by-step voltage regulators which have been in use for many years. In passing from one step to the next on such regulators, it is common practice to introduce a preventive coil or resistance in such a way that the two contact bars are bridged only through this preventive device.

In an armature winding arranged in this way, the working current is introduced through the brushes and the leads to the armature winding proper. After entering the winding, the

current does not pass through the resistance leads because the connections between coils are made beyond these leads. In consequence, only a very small number of these leads are in circuit at any one time, when the armature is in motion all the leads carry current in turn so that the average loss in any one lead is very small. As the brush generally bridges across two or more commutator bars, there is usually more than one lead in circuit, but generally not more than three. When the brush is bridging across two bars, there is not only the working current passing into the two leads connected to these two bars, but there is the local current, before described, which passes in through one lead, through an armature turn, then back through the next lead to the brush. There are losses in these two leads due to these two currents. By increasing the resistance, the loss due to the working current is increased, but at the same time the short-circuit current is decreased. As the loss due to this latter is equal to the square of the current multiplied by the resistance, it is evident that increasing this resistance will cut down the loss due to the local current in direct proportion as the resistance is increased. When the working current is much smaller in value than the short-circuit current, an increase in the resistance of the leads does not increase the loss due to the working current as much as it decreases the loss due to the short-circuit current. Both theory and practice show that when the resistance in the leads is so proportioned that the short-circuit current in the coil is equal to the normal working current, the total losses are a minimum. Calculation, as well as experience, indicates that a variation of 20% to 30% at either side of this theoretically best resistance gives but a very slight increase in loss, so there is considerable flexibility in the adjustment of this resistance. The resistance of the brush contacts and of the coil itself must be included with the resistance of the leads in determining the best value. In practice it is found that with ordinary medium-resistance brushes, the resistance in the leads themselves should be about four or five times as great as the resistance in the brush contact and the coil; that is, we usually calculate the total necessary resistance required and then place about 70% or 80% of it in the leads themselves. When leads of the proper proportion are added to the motor, it is found that practically twice as high field flux can be used as before with the same sparking and burning tendency as when the lower flux is used without such leads. But even with six

to eight volts per commutator bar as a limit, we are greatly handicapped in the design of the motors, especially when the frequency is taken into account. This limited voltage between bars also indicates at once why single-phase railway motors are wound for such relatively low armature voltages. Direct-current railway motors commonly use from 12 to 20 volts per commutator bar, or from 2 to 2.5 times the usual practice on alternating-current motors. With this low voltage between bars in alternating-current machines, with the largest practicable number of bars, the armature voltages become 200 to 250, or about 40% of the usual direct voltages. The choice of low voltage should, therefore, not be considered as simply a whim of the designers; it is a necessity which they would gladly avoid if possible.

Assuming preventive leads of the best proportions, let us again compare the current to be commutated in an alternating-current motor with that of the direct-current. Considering the ammeter reading as 100, the working alternating current has a maximum value of 140 and in addition there is a short-circuit current of same value. Even under this best condition, the alternating-current motor must commutate a current several times as large as in the corresponding direct-current motor. The design of such a motor, therefore, is a rather difficult problem, even under the best conditions.

While resistance leads theoretically appear to give the most satisfactory method for obtaining good starting and slow-speed running conditions, yet other methods have been proposed. The only one of any practical importance is that in which the short-circuit voltage is reduced at start and at slow speed by sufficiently reducing the field induction. As this reduced field induction would give a proportionately reduced torque, it is necessary at the same time to increase the armature ampere-turns a corresponding amount above normal. This is only a part solution of the problem, however, for the decrease in short-circuit current by this means is partly offset by the increase in the working current, so that the total current to be commutated is not reduced in proportion to the field flux. Where the period of starting and slow running is very short, this method is fairly successful in practice. However, with this arrangement it is rather dangerous to hold the motor at standstill for any appreciable length of time, for in such a case the large short-circuit current is confined to a single coil and the

effect is liable to be disastrous if continued for more than a very short period. With this method of starting, the total current handled by the brushes will usually be at least two to three times as great as when preventive leads are used.

The preceding statements refer mainly to starting or slow-speed conditions. When it comes to full-speed conditions, however, there are various ways of taking care of the commutation. One of these methods is based on the use of preventive leads, as described; the other methods depend upon the use of commutating poles or commutating fields in one form or another.

It is evident, from what has been said, that at start the preventive leads which reduce the short-circuit current to low values will also be effective in a similar manner when running at normal speed Such a motor with proper proportion of leads will, in general, commutate very well at full speed when the starting conditions have been suitably taken care of Nothing further need be said of this method except that the tests show that the short-circuit current has considerably less value at high speed than at start.

The other methods of commutation at speed, involving commutating poles and commutating fields, necessarily depend upon the armature rotation for setting up a suitable electromotive force in the short-circuit coil to oppose the flow of the short-circuit current. As the electromotive force in the short-circuited coil is a direct function of the field flux, and is independent of speed, while the correcting electromotive force is a function of the armature speed, it is evident that either the commutating pole can produce the proper correction only at one particular speed, or the strength of this commutating pole must be varied as some function of the speed Usually the strength of these poles is made adjustable with a limited number of adjustments and approximate compensation only is obtained on the average. In the Siemens-Schuckert motor the commutating poles are of small size and placed between the main poles. These are for the purpose of obtaining commutation when running. In addition the armature is provided with preventive leads for improving the operation at start and at slow speed. In the Alexanderson motor, according to published description, no separate commutating poles are provided, but the edges of the main poles are used as commutating poles, the armature coil having its throw shortened until its two sides come under the edges of the main poles. In this motor the field

is weakened and the armature ampere-turns are increased while starting The commutating-pole scheme in this motor is, in some ways, not as economical as in the Siemens-Schuckert arrangement, as the motor requires a somewhat higher magnetization with a consequent reduction in power-factor The Winter-Eichberg motor is quite different in arrangement from any of those which I have mentioned I will not attempt to describe this motor in full, but will say that it has two sets of brushes in the armature, one of which is short-circuited on itself, and carries the equivalent of the working current in the types I have described, while the other carries the magnetizing or exciting current which is supplied to the armature winding instead of the field. The arrangement is such as to give practically the same effect as a commutating pole or commutating field. When starting, the field flux is decreased and the armature ampere-turns increased

All of the above motors are nominally of low armature voltage and all of them appear to commutate reasonably well at speed. Two of them use the full-speed induction at start, while the other two use reduced induction and increased armature ampere-turns at start.

There has been considerable discussion during the last year or two regarding the most suitable frequency for single-phase commutator type motors It may therefore be of interest to consider what effect reduction in frequency would have on the commutation, output, and other characteristics of the motor.

The short-circuit voltage, as I have stated before, is a function of the amount of field flux and of the frequency. For a given short-circuit voltage the induction per pole can be increased directly as the frequency is decreased If a certain maximum induction per pole is permissible at 25 cycles, then with 12.5 cycles, for example, the induction per pole may be double, with the same short-circuit voltage. This would at once permit double output if the saturation of the magnetic circuit would permit the doubling of the induction. But on 25-cycle motors, as usually built, we work the magnetic flux up to a point just on the verge of saturation, so to speak, as indicated in Fig. 3. It is evident that double induction, under such conditions, would not be practicable unless the 25-cycle motor had been worked at an uneconomically low point. However, an increase of 30% to 40% in the induction would appear to be obtainable, but a large increase in excitation is required. With but 30%

to 40% higher induction, and with the frequency halved, the short-circuit voltage would be but 65% to 70% of that with 25 cycles or, in other words, the voltage per turn in the field coil is but 65% to 70%. As the higher induction raises the armature counter electromotive force the field electromotive force can be increased in proportion for the same power-factor, or can be 30% to 40% higher than with 25 cycles. As the total field voltage, therefore, can be 30% to 40% higher, and the voltage per field turn is but 65% to 70%, it is evident that the number of field turns can be doubled without changing the

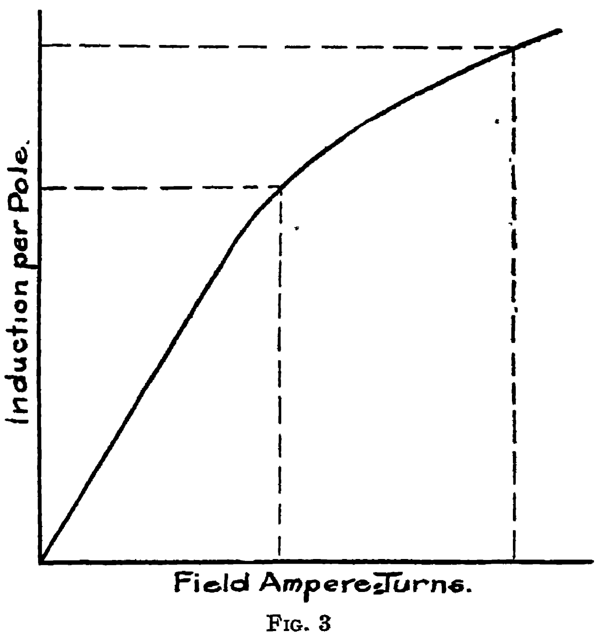


Fig. 3

ratio of the field inductive volts to the armature electromotive force. In other words, the field turns can be doubled if the frequency is halved. With the double field turns the field excitation can therefore be doubled, which is the requirement for the increased induction shown in Fig. 3. It is thus evident that halving the frequency will permit higher pole inductions, and therefore higher torque and output, with lower short-circuit voltage and better commutating conditions throughout. Also, this higher field induction is not necessarily accompanied by an increased iron loss, for the lower frequency of the alternating

flux compensates for this. On the above basis it may be asked why a reduction to 15 cycles is proposed instead of to 12 5, or even to 10 cycles. There are several reasons for the choice of 15 cycles.

1. The motor can be worked up to so high a saturation at 15 cycles that there is relatively small gain with a reduction to 12 5 cycles, which would be about the lowest frequency to consider when the transformers and other apparatus is taken into account

2 As the torque of the single-phase motor is pulsating instead of being constant, as in a direct-current machine, there is liability of vibration as the frequency of the pulsation is decreased. This effect becomes more pronounced the larger the torque of the motor, and is, therefore, of most importance in the case of a large locomotive Experience shows that this tendency to vibrate can be damped out effectively in very large motors with a frequency of 15 cycles, but becomes more difficult to suppress as the frequency is further reduced. This is, in reality, one of the fundamental reasons for keeping up to 15 cycles instead of reducing to 12 5 or lower.

3. The lower the frequency the heavier the transforming apparatus on the car or locomotive. It is probable that with 12½ cycles instead of 15 cycles, the increase in weight and cost of the transforming apparatus would about counter-balance the decrease in the same items in the motors themselves, although the efficiency and power factor of the equipment would be slightly better with the lower frequency.

4. As synchronous converters will be used to some extent in connection with the generating plants for single-phase systems in order to feed existing direct current railways, the frequency of 15 cycles will be slightly more favorable than 12.5 as regards cost of the converters and the step-down transformers The same will be true if motor-generators are used for transforming to direct current, also for induction motors.

Against the choice of 15 cycles may be cited the fact that there are other frequencies which represent a better ratio to 25 cycles when frequency-changers are to be taken into account. A low-frequency railway generating plant may require to tie up with some existing 25-cycle or 60-cycle plant; this can be done by interposing frequency-changers. Or it may be desired to obtain a lower frequency with a single-phase current from some existing higher frequency polyphase plant, By inter-

posing the frequency-changer the single-phase railway load will not exert any unbalancing effect on the polyphase supply circuit, and at the same time the railway circuit can be regulated up or down independently of the three-phase generator circuit. In case the three-phase plant is operated at 25 cycles, then a two-to-one ratio of frequencies; that is, 12.5 cycles on the railway circuit, would give the best conditions as regards choice of poles and speeds in the frequency-changer sets A five-to-three relation is given by 15 cycles, which is not nearly as good as the two-to-one ratio. A frequency of 16⅔ cycles would give a three-to-two ratio, which represents considerable improvement over the five-to-three ratio Therefore, this slightly higher frequency may prove of advantage in some cases. The choice of this frequency, however, does not mean a new line of apparatus; for a well designed line of 15-cycle motors tranformers, etc, should operate very well on a 16⅔-cycle circuit without any change whatever

When transforming from 60 cycles, however, the 15 cycle gives a four-to-one ratio which is very good, and neither 12.5 nor 16⅔ cycles is very satisfactory. Therefore this 15-cycle frequency represents the best condition in transforming from 60 cycles, and fairly good conditions for transforming from 25 cycles; and by operation of 15-cycle apparatus at 16⅔ cycles a very good transformation ratio is obtained from 25 cycles. It may be of interest to recall that the old Washington, Baltimore and Annapolis Railway, which was the first road contracting for single-phase commutator motors, was laid out for 16⅔ cycles. There was considerable criticisms at that time of the use of this frequency, but the statement which I have just made shows one very good reason for this frequency A second reason is that 16⅔ cycles per second is 2000 alternations per minute, which permits a steam turbine driving a two-pole generator to use a speed of 1000 rev. per min., which is a very good one for large turbo-generators.

I have gone into the question of induction and frequency as affecting the commutation and torque. I will now take up the question of power-factor in the single-phase commutator motor In a direct-current motor we have two electromotive forces which add up equal to the applied electromotive force, namely, the counter electromotive force due to rotation of the armature winding in the magnetic field, and the electromotive force absorbed in the resistance of the windings and rheostat.

In the alternating-current motor there are these two electromotive forces, and there is also another one not found in the direct-current machine, namely, the electromotive force of self-induction of the armature and field windings due to the alternating magnetic flux in the motor This inductive electromotive force exerts a far greater influence than the ohmic electromotive force for it has much higher values

The inductive electromotive force lies principally in the main field or exciting winding of the alternating-current motor There is a certain voltage per turn generated in the field coils, depending upon the amount of the field flux and its frequency, as stated before. This electromotive force per field turn is practically of the same value as the short-circuit electromotive force generated in the armature coil, as already referred to. I have stated that a short-circuit voltage of three or four volts per armature turn gave prohibitive designs and that it was necessary practically to double this This means that the field coils also have six to eight volts per turn generated in them The total number of field turns must, therefore, be very small in order to keep down the field electromotive force, for this represents simply a choke-coil in series with the armature. If the armature counter electromotive force should be 200 volts, for instance, which is rather high in practice with 25-cycle motors, then a field self-induction of half this value would allow about 14 turns total in the field winding. Compare this with direct-current motors with 150 to 200 field turns for 550 volts, or 60 to 80 turns for 220 volts The alternating-current 25-cycle motor, therefore, can have only about 20% to 25% as many field turns as the ordinary direct-current motor. This fact makes it particularly hard to design large motors where there must be many poles. In the single-phase motor the induction per pole being limited by the permissible short-circuit voltage, it is necessary to use a large number of poles for heavy torques; but the total number of field turns must remain practically constant on account of the self induction, while in reality the number of turns should be increased as the number of poles is increased. With a given number of poles we may have just sufficient field turns to magnetize the motor up to the required point; but if a large number of poles should be required, then we at once lack field turns and must either reduce the field induction, and thus reduce the output, or must add more field turns and thus get a higher self-induction or choking action in the

field, with a consequent reduction in power-factor Here is where a lower frequency comes in to advantage, for, as I showed before, with the same relative inductive effect, the field turns can be increased directly as the frequency is decreased The use of 15 cycles thus permits 67% more field turns than 25 cycles and raises our permissible magnetizing limits enormously This problem is encountered particularly in gearless locomotive motors of large capacity. For increased capacity the driving wheels are made larger, thus permitting a larger diameter of motor, the length, axlewise, being fixed. But with increased diameter of drivers, the number of revolutions is decreased for a given number of miles per hour. With 25-cycle motors we soon encounter the above mentioned limiting condition in field turns; beyond this point the characteristics of the motor must be sacrificed, and even doing this we soon reach prohibitive limits By dropping the frequency to 15 cycles, for instance, we change the whole situation. The induction per pole can be increased and the number of poles, if desired, can also be increased. The practical result is that, in the case of a high-speed passenger locomotive with gearless motors, a 700-h p. 15-cycle motor can be got in on the same diameter of drivers as required for a 500-h.p. 25-cycle motor. Also a 500-h.p. 15-cycle motor goes in on the same drivers as a 360-h.p., 25-cycle motor. At the same time these 15-cycle motors have better all round characteristics than the 25-cycle machines as regards efficiency, power-factor, starting, over-load commutation, etc.

Returning to the design of the motor, there is one other electromotive force of self induction which may be considered; namely, that generated in the armature winding and in the opposing winding in the pole face, usually called the neutralizing or compensating winding

Fig. 4 shows a section of the field and armature corresponding to the usual direct-current motor, or an alternating-current motor without compensating winding. In the direct-current motor the armature ampere-turns lying under the pole face tend to set up a local field around themselves, producing what is known as cross-induction. This produces no harmful effect except in crowding the field induction to one edge of the pole, thus shifting the magnetic field slightly and possibly affecting the commutation in a small degree. But if the armature is carrying alternating current this cross flux will generate an electromotive force in the armature winding, and this will be

added to the field self-induction, thus increasing the self-induction or choking action of the machine. As the armature turns on such motors are much greater, in proportion, than the field turns, it is evident that the ampere-turns under the pole face can exert a relatively great cross-magnetizing effect. This high cross-magnetization generates a high armature self-induction which may be almost as much as the field self-induction. Further, this great cross-induction would tend to shift the magnetic field quite appreciably, thus affecting the commutation to some extent.

To overcome this serious objection, the neutralizing winding is added. This is a winding embedded in the pole face and so

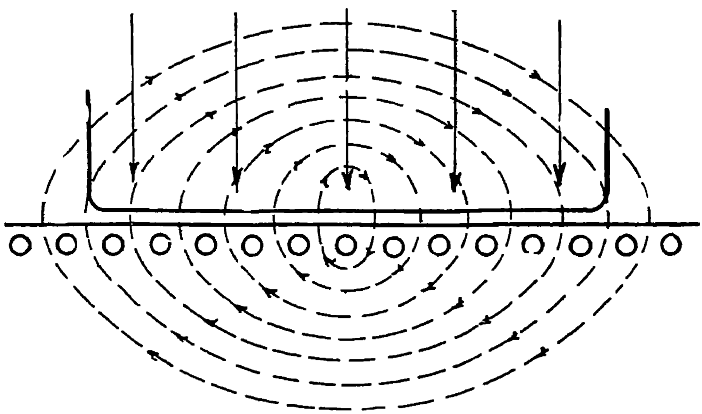


FIG. 4

arranged that it opposes the armature cross-magnetizing action. The arrangement is shown in Fig. 5. As it opposes and thus neutralizes the cross-induction set up by the armature winding, it eliminates the self-induction due to the cross-magnetization. It also prevents shifting of the magnetic field and thus eliminates its injurious effect on commutation. As the cross-flux is practically cut out the armature winding becomes relatively non-inductive. There is, however, a small self-induction in the armature and neutralizing windings, due to the small flux which can be set up in the space between the two windings, they being on separate cores with an air-gap between.

I have stated that the field turns of the alternating-current motor can be only 20% to 25% as many as in ordinary direct-

current practice. It may be questioned how the field can be magnetized with so few field turns. This has been one of the most difficult problems in the motor. Obviously, one solution would be the use of a very small air-gap, but in railway practice there are objections to making the air-gap unduly small. Furthermore, if the armature has large open slots, as shown in Fig. 6, experience shows that a reduction in the clearance between the armature and field iron does not represent a corresponding decrease in the effective length of the air-gap, due to the fact that the fringing of the magnetic flux from the tooth tip of the pole face changes as the air-gap is varied. The most effective construction yet used consists in making the armature slots of the partially closed type as in the secondary of an induction motor. This is shown in Fig. 7.

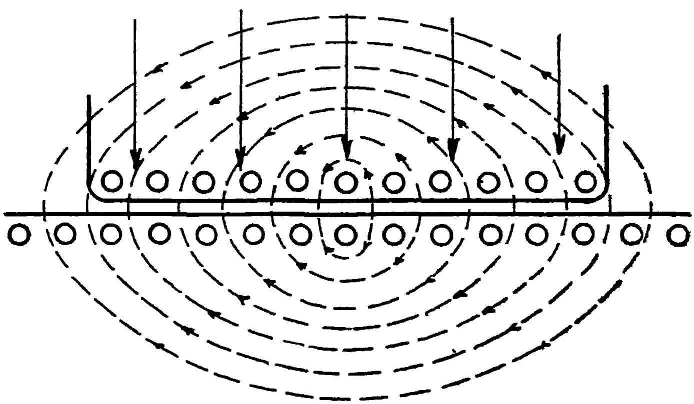


FIG. 5

With this construction practically the whole armature surface under the pole becomes effective, and the true length of air-gap is practically the same as the distance from iron to iron. With the increased effective surface, due to this construction, the length of air-gap need not be unduly decreased, which is of considerable importance in railway work.

A further assistance in reducing the required field turns is the field construction used in the single-phase motor. The magnetic circuit consists of laminations of high permeability and usually without joints across the magnetic path. The iron is also worked either below the bend in the saturation curve or, at most, only slightly up on the bend, except in the case of very low frequency motors where more field turns are permissible.

Taking the whole magnetic circuit into account, on 25-cycle motors about 80% of the whole field excitation is expended in the air-gap, while in direct-current motors, even with a much larger air-gap, as much as 40% to 50% of the magnetization may be expended in the iron and in the joints.

This armature construction with the partly closed slots has been found very effective in large, slow-speed, single-phase motors in which a relatively large number of poles is required. This construction is used on the New Haven 250-h p., 25-cycle

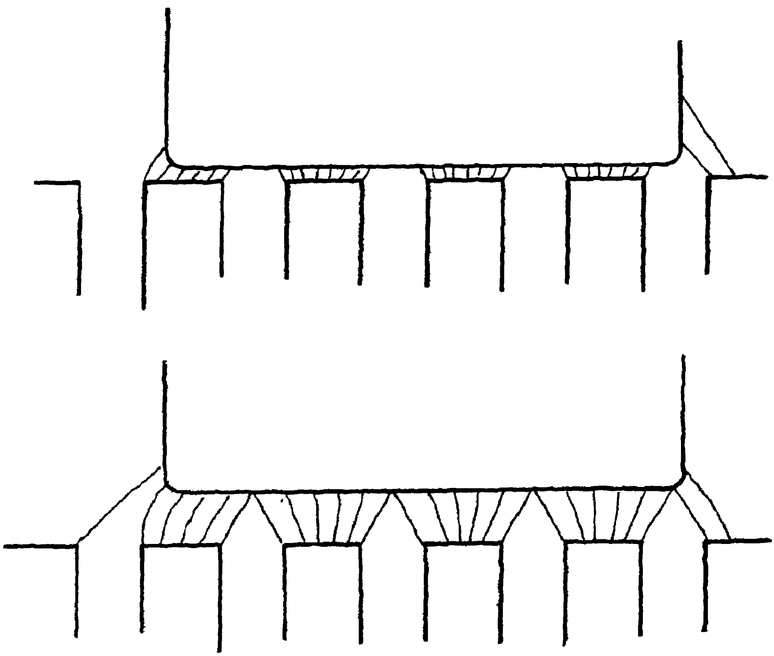


FIG. 6

motors; also on the 500 h.p., 15-cycle motor on the Pennsylvania locomotive exhibited at Altantic City at the Street Railway convention, last October. Geared motors for interurban service can be constructed with ordinary open slots with bands, and many have been built that way. The semi-closed slot, however, allows more economical field excitation.

It may be asked what the objection is to low power-factors on single-phase railway motors, aside from the increased wattless load on the generating station and transmission circuits. There is an objection to the low power-factor in such motors,

a very serious one. This lies in the greatly reduced margin for overload torque in case the supply voltage is lowered. In railway work it is generally the requirement of abnormal loads or torques which causes a reduction in the line voltage; that is, the overload pulls down the trolley voltage just when a good voltage condition is most necessary. This is true of direct current as well as alternating current. In the direct current motor, however, such reduction in voltage simply means reduced speed but in the alternating current motor the effect may be more serious.

To illustrate, assume a motor with a power-factor of 90% at full load. The energy component of the input being 90%,

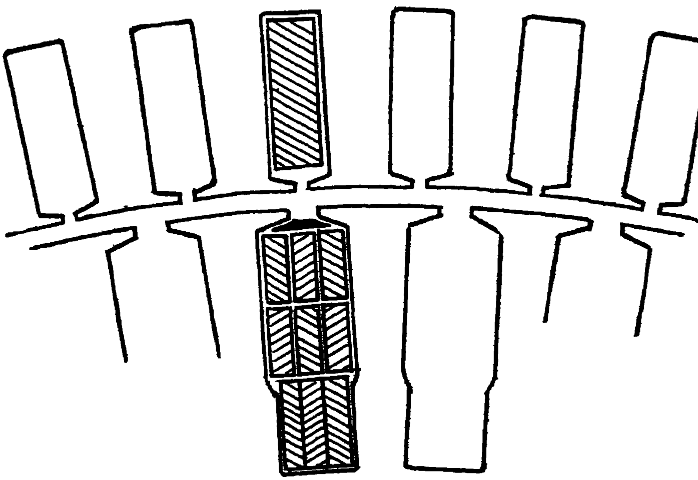


Fig. 7

the inductive component is about 44% or, putting it in terms of electromotive force the inductive volts of the motor are 44% of the terminal voltage. Neglecting the resistance of the motor, a supplied electromotive force of 44% of the rated voltage would just drive full-load current through it and develop full-load torque. With full voltage applied the motor could develop from five to six times full-load torque. Under abnormal conditions a drop of 30% in the line voltage would still give sufficient voltage at the motor terminals to develop two and one half to three times full-load torque. Let us next take a motor of 80% power-factor at full load. The inductive voltage would then become 60% of the terminal voltage, and therefore 60% of the rated voltage must be applied to send full-load current

through the motor. This neglects the resistance of the motor, which, if included, means that slightly more than 60% of the voltage is required. With full voltage applied, this motor would develop about three or four times the rated torque. With 30% drop in the line voltage the motor could develop from one and one half to two times rated torque, which is hardly enough for an emergency condition

Taking, next, a motor with 70% power-factor at full load it would require 70% of the rated voltage to send full-load current through the motor; with 30% drop in line voltage the motor could just develop full-load torque, and even with 15% drop it would develop only about one and one half times torque. As 15% drop is liable to occur on any ordinary system, this latter motor would be a very unsafe one.

It is evident from the above that it would be bad practice in railway work to install motors with very low full-load power-factors. In general, the higher the power-factor the more satisfactory will be the service, other things being equal.

I have endeavored to explain some of the problems which have been encountered in the design of single-phase commutator railway motors of sizes suitable for all classes of railway service. Here is a type of machine which has been known for a great many years, but which, until the last few years, has been considered utterly bad. In a comparatively short time it has been changed from what was considered an unworkable machine to a highly satisfactory one and this has been accomplished, not by any radically new discoveries, but by the common-sense application of well known principles to overcome the apparently inherent defects of the type. As an indication that the motor is making progress in the railway field, I will mention that the first commercial single-phase railway motors have not been in use more than four or five years, and yet at the present time there have been sold by the various manufacturers in this country and Europe, a total capacity of approximately 200,000 to 250,000 h.p., a very considerable part of which has been put in operation. Considering that the motor was a newcomer in a well established field, the above record is astonishing. However, it may be safely predicted that what has been done in the last five years will hardly make a showing compared with what will be done during the next five years, for the real field for such motors, namely, heavy railway work, has hardly been touched.

COMPARISON OF SERIES AND REPULSION TYPE A. C. COMMUTATOR MOTORS

FOREWORD—This is part of a discussion by the author, of papers by Dr. Steinmetz and Mr. Slichter before the American Institute of Electrical Engineers, January 2d, 1904. The major part of the author's discussion covered the comparison between the series and repulsion type motors, in which he showed that the repulsion type was simply a series type motor with a transformer added. The several references to Mr. Slichter's paper given in the discussion have but little bearing on the technical matter contained but could not be eliminated without considerable remodeling of the paper.—(Ed.)

Discussion of Steinmetz and Slichter Papers

IN the paper presented before the American Institute of Electrical Engineers, in September, 1902, the speaker called attention to the fact that there were but two types of single-phase alternating-current motors having suitable characteristics for railway service; viz., that called the "Series Type," and the "Repulsion Type." Attention was called to the fact that both motors have suitable characteristics for railway service, as both automatically give variable-speed characteristics with changes in load. That paper primarily described a single-phase railway system, and the motor formed but an element in the general system. It was a very general opinion at that time that the success of the commutator type of motor for large sizes was doubtful, and the sparking feature was considered a fundamental source of trouble. It was generally conceded that if a motor with series characteristics could be made to operate successfully, it would be a great step in advance in the railway field.

Since that time single-phase railway systems have been more fully developed. Practically, no departures from the general system then indicated have been furnished, and the types of motors developed have been along the lines of the two motors indicated in that paper.

Up to the present time the only suitable motors suggested for this work have been of the commutator type, and have been those having series characteristics. The speaker has suggested that all these motors can be considered broadly under the one class of series motors, as they all have the series characteristics

of the direct-current series motor. The speaker further suggested that they be sub-divided into the "Straight-Series" type and the "Transformer-Series" type. The transformer-series could also be arranged in two classes; viz., one in which the armature or field is supplied by an external transformer, and one in which the transformer is placed in the motor itself, this latter is the repulsion type of motor.

Figs 1, 2, and 3 illustrate the three classes. Fig 1 being the straight-series, Fig 2 the transformer-series and Fig. 3 the repulsion motor Fig 2 would be considered as a true series motor, although the armature and field are not directly in series, yet most of the characteristics described as belonging in the repulsion

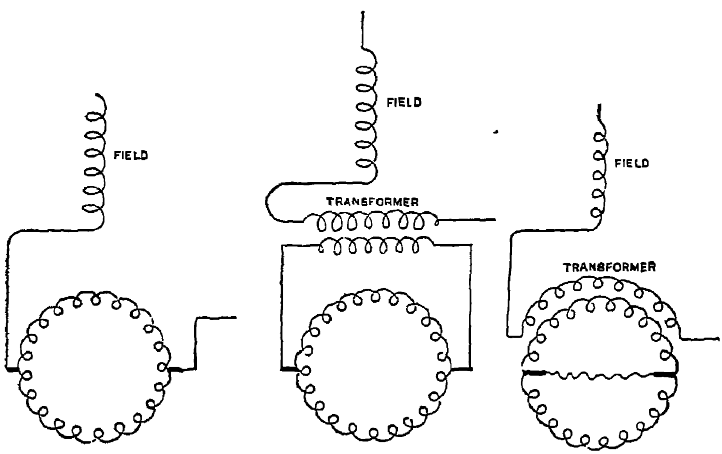


FIG 1. FIG 2 FIG 3

motor apply directly to the transformer motor shown in the figure. Comparing the relations of these motors, viz., the straight-series and the repulsion motor, we will first take up the straight-series.

In this motor, if properly designed, two pressures can be considered; viz., that across the field circuit, and that across the armature circuit. The armature pressure can be made practically non-inductive so that the input of the armature will represent practically true energy. The pressure across the field is practically at right angles to the armature pressure, and represents very closely the wattless component supplied by the motor. The resultant of these two pressures will then be the line pressure. The power-factor of the motor when running is represented prac-

tically by the pressure across the armature winding, increased slightly by the losses in the field-core and winding. Therefore, for high power-factors it is important that the pressure across the armature circuit be made as high as possible, relatively to the applied pressure, and that across the field as low as possible.

There are three ways in which to increase the pressure across the armature; viz., by increase in speed, by increase in the number of wires in series on the armature, and by increase in flux through the armature.

By increase in speed and increase of the wires in series, the armature pressure will be increased without affecting the field pressure, and therefore the ratio of the armature pressure to the line pressure is increased. Increasing the flux in the armature also increases the flux in the magnetizing-coil in the field, and the pressures of both are increased. Therefore this increase does not improve the power-factor of the machine.

Instead of increasing the armature pressure, the pressure across the field winding may be decreased; this can be done in two ways; viz., by reducing the turns in the field coil, or by reducing flux through the coil. Reducing the flux through the field reduces the flux in the armature winding also, and therefore represents no gain; reduction in field-turns, therefore, is the feasible means of reducing the field pressure. Reduction in field-turns can be accomplished in two ways; viz., by decreasing the effective length of air-gap in the motor, and by increasing the cross-section of gap. By making the gap very small the pressure across the field could be made very small compared with the line pressure, and extremely high power-factors could be obtained, whether the motor is of the straight-series or the repulsion type. Also by increasing the section of the air-gap the turns of the field can be decreased with a given total flux through the coil, and the power-factor can thus be very considerably increased. The first method, viz., decrease in gap, is limited by practical conditions which have been determined from long experience with direct-current work. It should be borne in mind when published descriptions of such motors are given, that the results, as regards power-factor, generally depend upon data which are not given in the description; such as the magnetic dimensions of the armature and field, the length of gap, etc. Therefore, a machine may be described as showing an extremely high power-factor, which may in practice not be a commercial machine, from the standpoint of American railway experience.

Increasing the section of air-gap without decreasing the length of gap also improves the power-factor, but makes a larger and heavier machine, as a rule.

Both these modifications reduce the ampere-turns in the field. The direction of the improvement in the armature was shown to be in increased armature ampere-turns with a given speed. It therefore follows that almost any result desired can be obtained as regards power-factor by increasing the armature ampere-turns and decreasing the field, or exciting ampere-turns. Reference will be made to this point in considering the repulsion motor.

It should be noted that in all these motors there should be but little saturation in the magnetic circuit and but few ampere-turns expended in saturation of the iron under normal conditions. This consequent low saturation in such motors leads to certain characteristics in the torque curves which have been cited this evening as an indication of superiority of alternating-current motors over direct-current motors; namely, a torque increasing approximately as the square of the current. In fact, this superiority of torque should be charged to the low flux-density of the motor rather than to the alternating current. If direct-current motors were worked normally at as low density as the alternating-current motor, then the direct-current motor would show better torque characteristics, and would be comparable with the alternating-current motor. This claim for a better torque in the alternating-current motor compared with the direct-current motor seems to be making a virtue of a necessity.

It is evident from what has been said that the power-factor of the straight-series motor can be made anything desired, it being a question of proportion between armature and field, length of air-gap, amount of material used, etc. In practice a compromise would naturally be made among the various characteristics, and a slight reduction in power-factor is probably of less importance than a corresponding reduction in size and weight. Also large clearance is probably of more importance than an extremely high power-factor at normal load. In practice it will be found that the armatures of such motors have a large number of ampere-turns compared with the fields, in order to obtain comparatively high power-factors with large air-gaps. The number of poles need not be made such that the product of the poles by the normal speed represents the frequency of the supply circuit; good series

motors can be made, and have been made, in which the number of poles were very much larger or much smaller than represented by this relation.

Taking up next the transformer type of motors—Fig. 2; the field is in series with the primary of the transformer, the secondary of which is connected to the terminals of the motor. I would call this a true series motor, although it is not a straight-series motor. In this motor the pressure across the armature can be made practically non-inductive and the pressure across the primary of the transformer will be practically non-inductive. The voltage across the field winding will have practically 90° phase relation to that across the primary of the transformers, and the magnetic field, set up by the field winding, will have a 90° relation in time to the magnetic field in the transformer, as in the repulsion motor. In this motor the voltage across the transformer will be highest at light loads and will decrease with load until zero speed is reached. At start there is lowest flux in the transformer and highest flux in the field winding. Such a motor will have speed-torque characteristics very similar to those of a straight-series motor, except as affected by the actions taking place in the transformer itself. If the transformer possesses no reactance, then at start the current in the armature should be the same as if connected as straight-series motor, and the conditions of torque at start should be the same. If the transformer has reactance, then at start the current in the armature will not be quite equal to the current which the armature will receive if coupled as a straight-series motor, assuming the transformer to have a 1 to 1 ratio. Neither will the armature current be exactly in phase with the field current; therefore the starting torque of a motor connected in this way will be slightly less than the torque of the same motor if connected in straight-series. This is on the assumption that the transformer is one proportioned for small reactance; but if the primary and secondary windings of the transformer should be on separate cores with air-gap between, then the reactances of the windings are considerably greater than in the above case. Therefore, we should expect a motor with such a transformer to give still lower torque than the straight-series with the same current supplied from the line.

In a repulsion motor the transformer is combined with the motor itself and the primary and secondary windings are upon

different cores with an air-gap between. The starting conditions of such a motor as indicated above should be poorer than the straight-series motor, or for the same starting torque somewhat greater apparent energy should be required. It stands to reason that applying the current directly to the armature winding should give greater ampere-turns and better phase relations than generating this current in a secondary circuit, and not under ideal transformer conditions. The tests which have been made, as well as the results shown in the curves of the papers given tonight indicate this. It is to be noted that the torque curve is not the same shape near the zero speed point as the torque curve of the series motor.

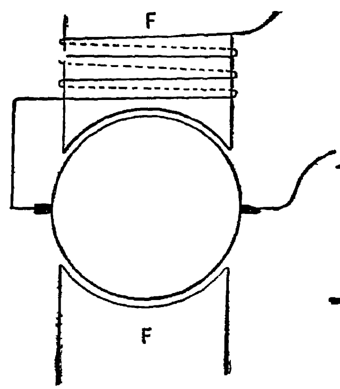


FIG 4.

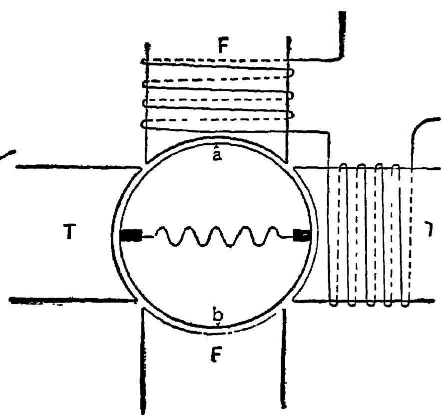


FIG 5.

Series motors and repulsion motors may be indicated in the simple form shown in Figs. 4 and 5. In the diagrams of the repulsion motor (Fig. 5), two field-poles *FF*, are shown, and two transformer-poles, *TT*. To obtain high power-factors on such a motoı the ampere-turns in *T* must be very much greater than in *F*, which means that the ampere-turns in the secondary or armature are much greater than in the exciting field, as in the series motor. The high power-factor obtained with these motors is therefore due principally to the small ampere-turns in the field and the small pressure across the field.

For ınstance, with brushes set at an angle of 16°, from the primary or resultant field, the ratio of armature to exciting field-turns would be almost 5 to 1, a ratio which will also permit of extremely high power-factors in well-designed straight-series

motors over wide ranges of speed. To this feature should be credited the good power-factors claimed for the repulsion motor. In either the series or repulsion type of motors, high power factors, especially at low speeds, are directly dependent upon this fact of high ratio of armature to field, and with a high ratio, high power-factors should be obtained without crediting the result to leading currents in the armature. In the diagram of the repulsion motor, the line current indicated flows through both the field winding and the transformer winding. The primary current sets up a magnetic field in the exciting windings in phase with the line current. If it also set up a field in the transformer in phase with the line current, then the electromotive force generated in the armature winding due to rotation would have a 90° relation to the electromotive force set up by the transformer, and a correcting or magnetizing current would flow. This flow is in such direction that it corrects the relation between the two pressures in the armature by shifting the transformer magnetism one-quarter phase later than the exciting field magnetism. This armature corrective current may thus be considered as magnetizing the transformer, making the primary input to the transformer practically non-inductive; but this magnetizing or correcting current may be considered as flowing in a circuit at right angles to the field magnetic circuit, and having practically no effect on the field circuit. Therefore as a rough approximation, the exciting field may be considered to represent the wattless component of the input, and the transformer field the energy component, as in the series motor. As to the statement that the magnetizing current in the armature reduces the wattless component of the exciting field, the speaker does not accept it broadly. If this component is reduced, then another component of practically equal value is introduced somewhere else, for the power-factors obtained with such motors can be accounted for by the high ampere-turns in the armature winding, compared with the field or exciting ampere-turns. If the armature current improves the power-factor by diminishing the magnetizing or exciting field, then the curves in Figs. 1 and 4 of Mr. Slichter's paper should show it. The speaker has gone over both sets of curves calculating the wattless components from the power-factors. From this and other data in these curves, he finds that beginning near synchronous speed the wattless component in the motor goes up slightly faster than would be represented by the field excitation,

assuming it to be entirely wattless. Therefore, according to these curves, the power-factors at lower speeds are not quite as good as would be obtained by a field entirely inductive and the armature entirely non-inductive, in a straight series motor. These calculations are rather approximate, as the curves do not check at all well with each other. For instance, the output of the motor as represented by the input multiplied by the power-factor and by the efficiency, does not check with the output as represented by the product of speed by torque, in either set of curves, the discrepancies being as high as 10 percent. In Fig. 4, for instance, either the torque or the speed is too high for the lower speeds. Checking back on this curve, using either the speed and torque or the power-factor and efficiency for determining the output, the speaker finds that the wattless component in the motor at 190 revolutions is approximately 20 percent higher than it would be if the field excitation alone were wattless, assuming at 440 revolutions the wattless component is represented purely by field excitation; that is, from 440 to 190 revolutions the wattless component is increased 20 percent over that which would be represented by field excitation alone. This indicates that not only should the field excitation be considered as practically wattless, but that in addition there is a wattless component due to reactances in the armature windings.

The armature current can be split into two components, one of which is partly magnetizing and represents no torque. The other component is in phase with the field magnetism and therefore represents torque. The magnetizing or wattless element may be comparatively small, as the number of turns in the armature is relatively large, but the armature thus carries at times a slightly larger current than the straight-series motor.

A further inspection of the diagram (Fig. 5) indicates how the power-factor of the motor can be made very high at synchronous speed. At all speeds the pressure generated in the armature due to rotation in the field of F, is practically equal to the pressure generated by the transformer T, thus making zero pressure across the terminals. But also at synchronous speed the pressure generated by the exciting field acting as a transformer, between the points a b, will be practically equal to the pressure generated in the winding by rotation of the winding in the transformer field. Therefore across a b the pressure is practically zero with these conditions, but the frequency remains the same as that in

the field. If now the magnetizing current be supplied across the points *a b*, then the required ampere-turns for magnetizing the motor can be supplied at practically zero pressure, and the turns of the external magnetizing field can be omitted. Therefore, under this condition the wattless component is practically zero and the power-factor becomes practically 100 per cent. This is the method of excitation used on certain European single-phase motors in which high power-factors are claimed for full-load running. But this method of excitation does not improve conditions at start, as the same excitation will be required at standstill, whether the excitation be supplied to the armature or to the field. Therefore this method of excitation does not help the motor at that condition of load which is the severest on the generating and transmission system. It has the advantage of omitting the field exciting winding, but has the great disadvantage of requiring a double set of brushes on the commutator, with but half the distance between the brushes found in the straight-series or the ordinary repulsion motor. I do not believe that such methods of compensation are of sufficient advantage to overcome the complications attendant upon them.

At zero speed, both the straight-series and the repulsion motors have low power-factors and with equal losses in the motors, the repulsion should have slightly lower power-factor than the series. This question of power-factor at start is largely a question of internal losses in the motor at rest, and the repulsion motor in individual cases may show higher than the series motor, because it may be designed with higher internal losses. The real measure of effectiveness is not the power-factor at start, but the apparent input or kilovolt-amperes at start required for a given starting torque. With equally good designs of motors, the speaker's experience is that the kilovolt-amperes will be found to be considerably less with the straight-series than with the repulsion motor, due to the fact that the current is fed directly into the armature and not by transformer action, and therefore the conditions of phase-relation and amount of current in the armature windings are more favorable. Therefore it follows that in order to have the same kilovolt-ampere input for the same starting torque, the repulsion motor should have a smaller length of air-gap than the corresponding straight-series motor, or should have a greater section of air-gap, which means greater weight of motor. This is one of the conditions which has led the speaker

to the advocacy of the series motor rather than the repulsion motor, as he has considered this condition of starting of more importance than running; although he is satisfied that many of the running conditions of a well-designed series motor will be found in practice to be superior to those of an equally well-designed repulsion motor.

Referring again to Fig. 5, it will be noted that two fields are set up in such a motor, and that at synchronous speed these two fields are equal. In the straight-series motor there is but one field set up, the other being omitted. It is evident that the straight-series motor with the current supplied directly to the brushes can have a smaller section in certain parts of the magnetic circuit than is required for the repulsion motor, and that therefore the weight of material would be less, and the external

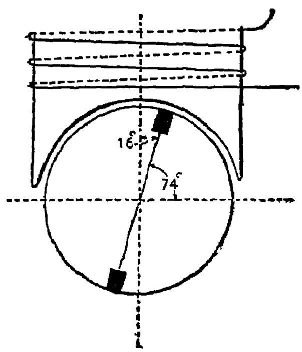


FIG 6.

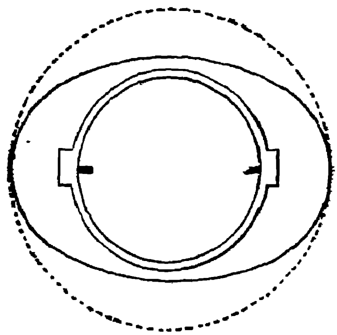
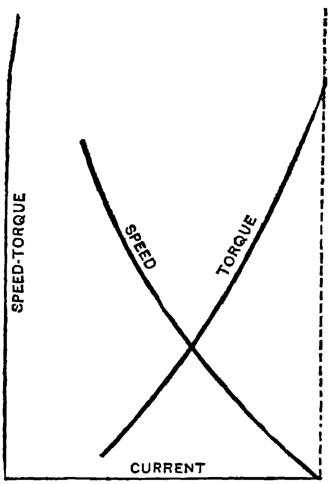


FIG. 7.

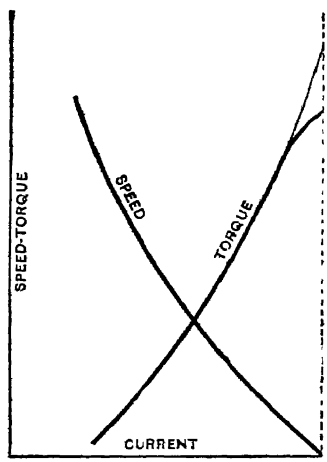
dimensions can be less. In Fig. 7 the heavy line represents outlines of series and the dotted line those of repulsion motor; therefore, it follows that for equally good designs and same frequency, the straight-series motor should be more compact, and should weigh less than the repulsion motor. It is reasonable to expect this, as the repulsion motor contains a transformer in addition to the other parts found in the straight-series motor. Futhermore, the transformer found in such a motor is one with an air-gap, and with the windings on two separate elements, and therefore cannot be so well proportioned as a separate transformer could be. Also, there is à transformer for each motor, and in a 4-motor railway equipment, for instance, there would be four transformers of smaller size against one larger transformer used with the series motor, this larger transformer having a

closed magnetic circuit, and of a highly efficient design compared with the transformers in the motors themselves.

A further point should be taken up in the comparison of these motors; viz , the current in the coil short-circuited by the brushes. This coil is a secondary to the field and the current in it is necessarily greatest at the period of strongest field. Therefore, this current will be greatest at the time of starting. If the repulsion motor and the straight series motor have the same field strength at start, then the short-circuited current should be the same in each But as the current is fed into the armature in the repulsion motor through transformer action, it will as a rule be found that



STRAIGHT SERIES MOTOR



REPULSION MOTOR

the starting field strength of such a motor is slightly greater and the starting armature strength slightly less for a given torque than is found in the straight-series motor having same ratio of armature to field windings. Therefore the short-circuit current at start will be somewhat larger for the repulsion motor than for the corresponding straight-series motor. This short-circuit current may be somewhat less near full speed than in the straight-series motor, but it is not the full-speed condition which is the serious one. The short-circuit current at start is one of the most serious conditions which confronts us in alternating-current motors, and is also of great importance where there is any considerable operation on low speeds. The speaker advocates

a type which he considers gives the easiest condition in this regard. This short-circuiting cannot be entirely avoided in any of the motors brought out without adopting abnormal and questionable constructions, although devices like narrow brushes, sandwich windings, etc., have been proposed. In certain foreign motors the brushes used are so narrow that they cover practically the width of one commutator-bar. As such motors are generally built with a very large number of bars, the brushes used are extremely narrow, being approximately 0.2 inch thick at the tip. This will undoubtedly lessen the short-circuiting, but simply transfers trouble to another point; a brush 0.2 inch thick is not practicable for commercial railway service; at high speeds, with only a moderately rough commutator, such brushes will be liable to chip and break; further, the brush on a street-car motor should bridge at least two bars to give good, smooth, brush operation; in practice, a 0 5 inch brush on motors of 100 h.p. should be used.

The sandwich winding, which consists of two or more windings side by side, will prevent short-circuiting at the brushes, but is only another way of transferring trouble to another point; it has been found in practice that it is difficult to run a sandwich winding without trouble at the commutator with direct current, without a tendency to blackening and pitting the commutator, and with alternating current this tendency to pitting and burning of the bars would be equally great.

As a rule, there is little difference between the operation of repulsion and straight-series motors as regards sparking, except that the repulsion motors generally have greater current in the short-circuited coil near zero speed, and therefore show greater tendency to heat and spark. At or near synchronous speed, there appears to be very little difference in the commutation, although the speaker has never given the repulsion motor the same test of long-continued service as he has in the case of the series motor. These series motors have never shown any tendency to give trouble on the commutator, and on an exhibition car equipped with four 100-h.p. motors, the commutators have never been sandpapered since the equipment has been put into service. This exhibition car is used principally for showing the accelerating properties of the motors; therefore, the speaker does not hesitate to say that the commutation of the straight-series motor will prove to be equal to that of the direct-current

motor. Wide brushes are used with it, such as have been used in street-railway motors.

It is well known that with large direct-current motors, especially when operated at very high speeds, there is a tendency to flash across the commutator, or to the frame of the motor, if the field circuit be opened for a period long enough to allow magnetism to drop to zero, and then the field be closed again. In this case there is a rush of current before the field has had time to build up, and this rush of current, together with field distortion, may cause serious flashing. In the alternating-current motor, whether of the straight-series or the repulsion type, this tendency should be entirely absent. In the straight-series motor the magnetism falls to zero once in each alternation, and therefore if this tendency existed, flashing would occur continuously. Furthermore, a properly designed straight-series motor can be short-circuited across the brushes without injury to the motor, and can continue to operate in this way; therefore, if the machine can be short-circuited in this way, there is evidently no tendency to maintain an arc.

Returning to the subject of power-factors it should be noted that high-power-factors are very frequently found in motors of low or only moderately good efficiency. This low efficiency to a slight extent explains the high power-factor in some motors, both polyphase and single-phase. Low efficiency means higher true energy expended, and with a given wattless component it means higher power-factor. It is the old problem of increasing the power-factor by wasting energy in a circuit instead of reducing the wattless component. The power-factor of any alternating-current motor can be very considerably increased by putting resistance in series with it. Instead of this resistance the internal losses of the motor may be made higher, which will accomplish the same results. The motor will therefore appear to have a higher power-factor than it really deserves, if efficiency of the motor is taken into account. If, for instance, the efficiency at 300 rev. shown in Mr. Slichter's Fig. 4 would be made as high as on direct-current motors, then the power-factors with the same magnetizing and other conditions, would have been approximately four percent lower. This lower power-factor would not have made any harder condition on the supply circuit, but actually would have made a somewhat easier condition, as the supply system would have furnished about eight percent less kilovolt-

amperes. For lower speeds this difference in power-factor will be greater, and less for higher speeds A high power-factor at start, obtained by the use of resistance in series with the motor by high internal losses which do not represent torque, is therefore a detrimental condition rather than a good one, as it means increased kilovolt-ampere expenditure for a given torque. This is merely given as an illustration showing that power-factor in itself is not a true indication of conditions, but must be accompanied by other data; this is not a criticism of these motors, but is a general condition, found to a greater or less extent in all alternating-current motors.

COMPARATIVE CAPACITIES OF ALTERNATORS FOR SINGLE AND POLYPHASE CURRENTS

FOREWORD—This article was prepared many years ago for the information of the younger technical men of the Westinghouse Company. It was considered of sufficient value by the Company to publish in pamphlet form, of which there were several editions from time to time. It should be considered as purely educational. Only the types of windings which were in use up to the time the paper was prepared, are included.—(Ed.)

THERE are a number of popular misconceptions regarding the relative polyphase and single-phase capacities which can be obtained from a given winding. For instance, there appears to be a half-formed opinion that a given winding connected for two-phase will give a slightly less output than when connected for three-phase; but, on the other hand, it seems to be generally assumed that the various three-phase windings all give the same rating.

Also, it is a widespread idea that when any polyphase machine carries a single-phase load the permissible rating, with the same temperature, is approximately 71 percent of the polyphase rating. While there are a few cases where this may be true, yet, in general, it is far from being the fact, as will be explained below.

This fallacy regarding single-phase ratings arose partly from early practice with polyphase machines, which were ofttimes designed with a view to carrying single-phase load almost exclusively. In consequence, the type of armature winding chosen was, in many cases, that which gave a high output on the single-phase, with some sacrifice in the polyphase rating, and the single-phase rating in many cases was a relatively large percent of the polyphase rating simply because the polyphase rating was less than could have been obtained with a different type of winding.

The 71 percent (or 70.71 percent) ratio of single-phase to polyphase ratings in a given armature arose partly from the fact that at these relative loads the total armature losses were practically equal. On old designs of machines, in many cases it could be assumed safely that with equal armature losses the temperature of the armature parts would be practically equal. This assumption

does not hold, in general, on modern designs of machines in which each individual part is proportioned for a specified result. The distribution of the armature losses is just as important as the total losses. If the temperature drop between the inside of the armature coil and the armature core is small compared with the temperature drop from the core to the air, then the temperature of the armature, or its rating, will depend largely upon its total losses, equal ventilation being assumed in all such comparisons If, however, the temperature drop from the coil to the iron, or from the inside of the coil to the outside, is relatively high, then the temperature limit may be fixed by the loss in an individual coil rather than by the total loss. This is particularly the case in high voltage

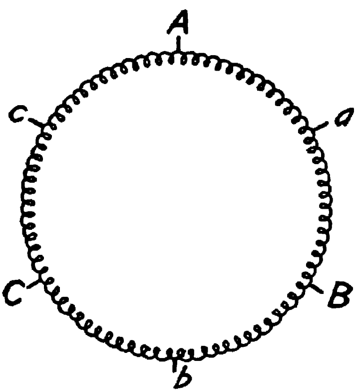


Fig. 1

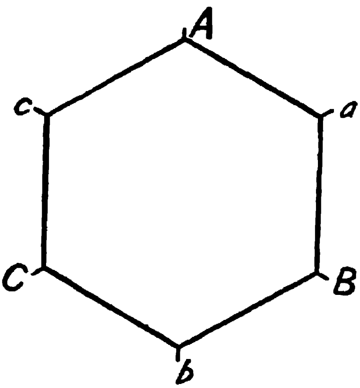


Fig. 2

machines where there is a considerable amount of insulation over the individual armature coils. Also, in many of the later designs of machines (especially turbo-generators) each armature coil is practically separated from all other coils, so that one coil can have but little direct influence on the temperature of its neighboring coils. In such an armature it is possible to completely roast out an individual coil or group of coils without seriously heating any other coils or groups of coils. It is obvious that in such a machine the loss in the individual coils is what fixes the rating of the machine, and not the armature loss as a whole. It is evident, therefore, that when a polyphase machine, with such a winding, is loaded single-phase, the maximum current which can be carried in any single coil must be the same for either polyphase or single-phase rating. As this type of winding is used in the majority of large capacity machines of the present day, the following comparison will show

the relative rating of such machines on polyphase and single-phase loading. Three-phase ratings will be considered first, because the great majority of modern machines are wound for three-phase.

Three-Phase Windings

All the various types of commercial three-phase windings with their current and voltage relations can be derived in a very simple manner from the consideration of a ring armature with its windings arranged in six symmetrical groups, each covering 60 degrees of the ring, which may all be closed together to form the ordinary closed winding, or which may be separated into either three or six groups and connected to form various delta and star types of windings.

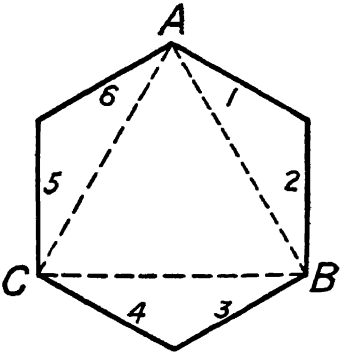


Fig. 3

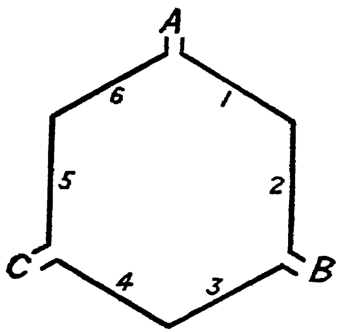


Fig. 4

Let Fig. 1 represent such a ring armature closed on itself and with six taps brought out, these being designated as A, a, B, b, C, c.

By connecting together the points Aa, aB, Bb, etc., as shown in Fig. 2, a six-sided figure is obtained, which represents the various voltage and phase relations which can be obtained with all commercial three-phase (and six-phase) windings. It will be noted that Aa and bC are of equal length and are parallel in direction. The length represents e. m. f. and the direction represents phase relation. Therefore, these two groups or legs are of equal e. m f.'s and of the same phase. The same holds true of aB and Cc, and of Bb and cA. Beginning at Aa, these groups have also been numbered consecutively from 1 to 6, so that in the following diagrams a given leg or group can be identified by number.

Fig. 3 is the same as Fig. 2 with three leads carried out from A, B and C to form the three terminals of a three-phase winding The dotted lines from A to B, B to C, and C to A represent the voltage and phase relations obtained from this combination This is known as a closed coil type of winding and is the standard arrangement of winding on a three-phase rotary converter. The comparative e m. f. values for this and other combinations will be given later

By opening the closed arrangement of Fig 2 at the points A, B and C, as shown in Fig. 4, then an open coil arrangement is obtained and the three parts resulting can be recombined in several ways, keeping the same voltage and phase relations of the individual parts.

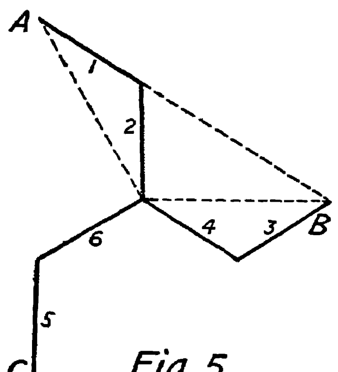


Fig. 5

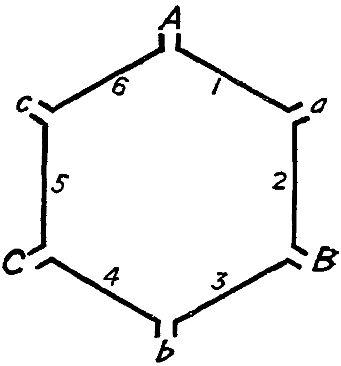


Fig. 6

However, only one of these combinations,—that shown in Fig. 5— has been used to any extent. This is one form of star winding which is sometimes used to give certain voltage combinations, as will be explained later.

By splitting Fig. 2 at six points instead of three, as shown in Fig. 6, various other open coil combinations of windings can be obtained while keeping each group or leg in its proper phase and voltage relations.

One of these combinations is shown in Fig. 7, in which the groups which are similar in e. m. f. and phase are connected in parallel and the three resulting combinations are connected to form a delta winding.

In Fig. 8 the two groups of similar phase are shown in series instead of parallel and connected to form a delta. Obviously

Fig. 7 and 8 are equivalent, except that the terminal e. m. f of one is double that of the other

By reconnecting the three components of Fig 7 in the manner

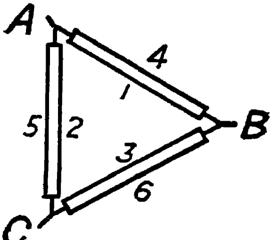


Fig. 7

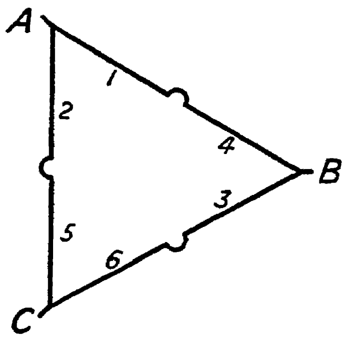


Fig. 8

shown in Fig. 9, a parallel star winding is obtained. Two arrangments are shown, one with all the legs connected together at the middle point, and the other with the two stars not connected at the middle.

Fig 10 is equivalent to Fig. 9 except that the two e. m. f.'s of

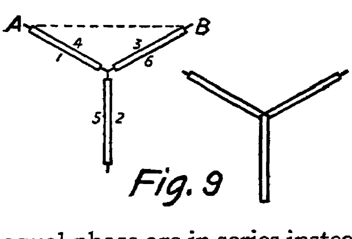


Fig. 9

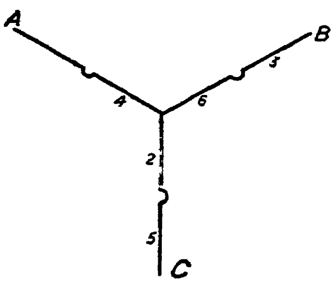


Fig. 10

equal phase are in series instead of in parallel, thus giving just twice the voltage of Fig. 9.

Six-Phase Windings

The foregoing covers all of the usual combinations for three-phase windings, open and closed coil types. The same general scheme may be used to illustrate the usual six-phase combinations of windings which are frequently used in connection with rotary converters.

In Fig. 3, a three-phase winding is shown with terminals at A, B and C. If three other terminals be formed by a, b and c, then a second three-phase winding is obtained. The dotted lines in Fig. 11 illustrate the voltage and phase relation of these two windings. This is the so-called double delta arrangement sometimes used with six-phase rotaries, the dotted lines representing the voltage and phase relations of the transformers which supply the rotary converters.

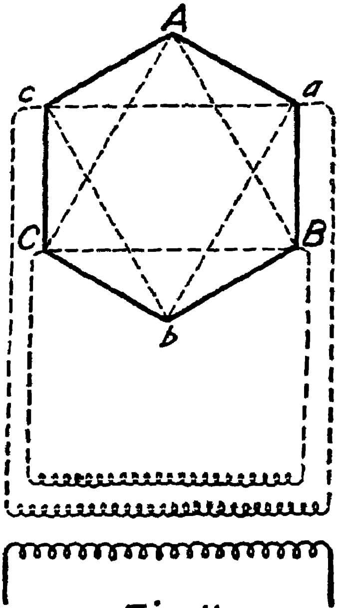


Fig. 11

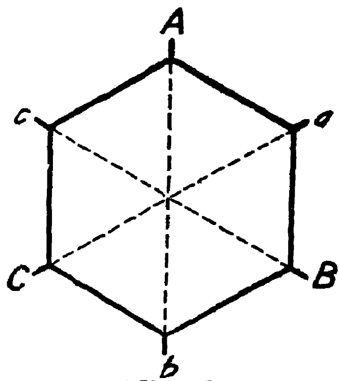


Fig. 12

It is evident that the voltage represented by ac is equal in value and phase to that represented by BC. Therefore, one transformer with two secondaries of equal value could be tapped across these two circuits. Similar arrangements can be applied to the other two-phase relations in this diagram.

In Fig. 2 it is evident that, if six terminals are used, a voltage can be obtained across Ab Similar voltages can be obtained across aC and Bc. These three voltages are equal in value but have the 60-degree relation to each other. It is evident therefore that three transformers connected to a three-phase circuit can have their secondaries connected to this winding across the indicated

points. This arrangement is indicated in Fig. 12, and is the so-called diametral connection of six-phase rotaries. The middle points of the transformer winding from these three circuits can be connected together, if desired.

Relative E. M. F. Obtained from the Foregoing Combinations

From an inspection of the above diagrams, and the application of but very little mathematics, all the e. m. f. relations of these various combinations can be readily obtained. In the following comparisons the magnetic field is assumed to be of such distribution that the e. m. f. waves will be of sine shape, as this greatly simplifies the various relations.

Let E represent the effective e. m. f. of any one of the six legs or groups in Fig. 2. Then, combining the various groups geometrically, taking into account the angular relation between the legs in the diagram, the various e. m. f.'s can be readily derived. The results are as follows:

In Fig. 3, the e. m. f. across AB, BC, etc., $= \sqrt{3} \times E = 1.732$ E.

In Fig. 5, the e. m.f. Ad is the same as AB in Fig. 3 and is therefore equal to $\sqrt{3} \times E$, but the e. m. f. AB in Fig. 5 is equal to $\sqrt{3} \times Ad$. Therefore, the e. m. f. of $AB = \sqrt{3} \times \sqrt{3} \times E = 3E$.

In Fig. 7, AB is evidently equal to one group or side of Fig. 2 and therefore the e. m. f. of $AB = E$.

In the same way the e. m. f. of Fig. 8 $= 2E$.

In Fig. 9 the e. m. f. Ad is evidently equal to E and the e. m. f. $AB = \sqrt{3} \times$ e. m. f. of Ad. Therefore the e. m. f. of $AB = \sqrt{3} \times E = 1.732\ E$, or same as Fig. 3.

In the same way the e. m. f. of AB in Fig. 10 = 2 times $\sqrt{3} \times E = 3.464\ E$.

For the six-phase combinations the following e. m. f.'s are obtained:

In Fig. 11 each of the deltas is the same as in Fig. 3 and therefore the e. m. f.'s are the same and are equal to 1.732 E.

In Fig. 12, Ab is geometrically equal to twice aB and the e. m. f. Ab is therefore equal to $2E$.

Three-Phase Capacities

It might be assumed from casual inspection that all of the different combinations of three-phase and six-phase would give

the same capacities when carrying the same limiting current per armature coil, or per leg. This however, is not correct, as will be shown by the following:

Let A equal the limiting current which can be carried by one coil or by one group of windings. This is not necessarily the current per terminal, but it is the current permissible in an individual coil without exceeding a certain prescribed temperature. Then the following ratings are obtainable with the above combinations of windings.

In Fig. 3 the rating $= 3A \times \sqrt{3} \times E = 5.196\ AE$.

In Fig. 5 the current per coil and per terminal $= A$. The e. m. f. becomes $A \times \sqrt{3} \times 3E = 5.196\ AE$. Therefore the three-phase ratings of the windings in Figs. 3 and 5 are equal.

In Fig. 7 the current in each leg of the delta is $2A$, as there are two groups in parallel, each carrying current A. As the e. m. f. across terminals is E, the rating becomes $3 \times 2A \times E = 6\ AE$.

In Fig. 8 the current per side or leg of the delta is equal to A and the e. m. f. is $2E$. The capacity therefore becomes the same as for Fig. 7 or $= 6\ AE$.

In Fig. 9 the current per terminal is $2A$ as there are two groups in parallel for each terminal. The e. m. f. across the terminals is $\sqrt{3} \times E$. The capacity is therefore $2A\ \sqrt{3} \times \sqrt{3}\ E = 6\ AE$.

The rating of Fig. 10 is also $6\ AE$, the same as Fig. 9.

In Figs. 11 and 12 the ratings can be determined by direct inspection from the following method of considering the problem:

In a closed coil, polyphase machine, for example, such as shown in Fig. 2, one circuit can be taken off from A and a, a second circuit from a and B, etc., and the total number of circuits which can be taken off corresponds to the number of armature taps. Each circuit can be considered as having its own rating. Therefore, the effective voltage of each of such circuits times the current per circuit, times the number of circuits, equals the rating. In Figs. 11 and 12 six circuits can be taken off, each with voltage E and carrying current A. The rating therefore becomes $6\ AE$. The same method could be applied to any other number of phases from closed coil windings.

It is evident from the foregoing that the same rating can not be obtained from the armature winding with all methods of connection. In those three-phase arrangements in which two groups of similar phase relations are thrown in series or parallel, the high-

est output is obtained. In those cases where two e m f.'s out of phase with each other are combined to form one leg of the three-phase circuit, it is evident that the resultant e. m. f. is at once reduced by such combinations and that the capacity of the machine is therefore reduced, simply because the most effective use of the windings is not obtained. The three-phase closed coil winding is therefore not as effective as the true delta or star type of winding. For this reason the closed coil winding is used in only those cases where some condition other than the current capacity itself is of greater importance. Otherwise, delta and star windings are always used, the star being preferred as it gives a higher voltage with a given number of conductors, or a smaller number of conductors for a given voltage, and is therefore somewhat more effective in the amount of copper which can be gotten into a given space

SINGLE-PHASE RATING—Any three-phase machine with one of the above windings can be used to carry single-phase load by using two of the three terminals. The single-phase e. m f.'s obtained will therefore be the same, in each case, as the three-phase. The current capacity per coil, or group, on single-phase can be no greater than on three-phase. On this basis, therefore, the following single-phase ratings are obtained with the above combinations:

Fig. 3, calling A and B the single-phase terminals, then with the limiting current A per coil, the windings 1 and 2 in the diagram will carry current A, and 3, 4, 5 and 6 will carry $\frac{1}{2}A$. The total current at the terminals will therefore be $1\frac{1}{2}A$ and the e. m. f. per terminal will be $\sqrt{3}\ E$. The single-phase rating then becomes $1.5\ A \times \sqrt{3}\ E = 2.598\ AE$. The corresponding three-phase rating is $3A \times \sqrt{3}\,E = 5.196\ AE$. The single-phase rating is therefore just 50 percent of the three-phase for this combination.

In Fig. 5, the current per leg is A, while the e. m. f. is $3E$. The single-phase rating therefore becomes $3\ AE$. The corresponding polyphase rating is $A \times \sqrt{3} \times 3E = 5.196\ AE$. The single-phase rating is therefore 57.7 percent of the polyphase rating

In Fig. 7 the total current in two legs is $2A$, while in the other four legs of the delta the total current is A. The total current at the terminals therefore becomes $3A$. The e. m. f. is E and therefore the single-phase rating becomes $3\ AE$. The corresponding three-phase rating is $6\ AE$. The single-phase rating is therefore 50 percent of the polyphase for a true delta winding.

The same holds true for Fig. 8.

In Fig. 9 the current per group is A and with two groups in parallel the current per terminal is $2A$. The e. m. f. across the terminals is $\sqrt{3}\ E$. The single-phase rating therefore becomes $2A \times \sqrt{3}\ E$ or $3\ 464\ AE$. The three-phase rating for the same combination is $6\ AE$. The single-phase rating therefore becomes 57.7 percent of the three-phase when a true star winding is used.

Fig. 10 gives the same results as Fig. 9.

It may be noted that in the three-phase star arrangement two legs are carrying all of the current, while the third leg is idle and could be omitted. This means that the active winding covers two-thirds of the armature surface, while an idle space of one-third the surface lies in the middle of the winding.

In the delta winding it may be noted that one leg, covering one-third the surface, is directly in phase with the single-phase e. m. f. and is therefore in its most effective position The other two legs carry current also, but are relatively ineffective as the e. m f.'s generated in these two legs are displaced 60 degrees in phase from the single-phase e. m. f. delivered. The delta arrangement therefore has two-thirds of its winding acting in a very ineffective manner. One-third of the winding is very effective. In the star arrangement, two-thirds of the winding is almost in phase with the terminal e. m. f. (being 86 6 percent effective), while one leg is entirely idle. The star arrangement is about 15 percent more effective than the delta arrangement.

The single-phase rating which can be obtained from the two six-phase combinations shown in Figs. 11 and 12 should also be considered. In either of these diagrams, if two opposite terminals, such as AB, be taken as the single-phase terminals, then the e. m f. will be $2E$. As each half of the winding can carry the current A, the total which can be handled is $2A$. The single-phase rating therefore becomes $4AE$. The corresponding polyphase rating is $6AE$. The single-phase rating is therefore 66.7 percent of the polyphase, or is higher than in any of the other three-phase combinations shown. It should be noted, however, that in order to obtain three-phase from this combination, transformers are necessary in order to transform from six-phase at the winding to three-phase on the line. Therefore, while this combination gives the highest single-phase and polyphase ratings, yet if three-phase is used on the transmission circuit, transformers must be interposed. Therefore, the highest obtainable rating of single-phase and three-phase from the same winding implies the use of transformers.

The high single-phase rating obtained in this case is due to the fact that the arrangement is equivalent to the star arrangement with the idle leg added, as illustrated in Fig. 13. The addition of this extra leg increases the terminal e. m. f. in the ratio of 100: 86.6, while the current per terminal remains the same. This arrangement, when used for both single-phase and three-phase, implies the use of a closed coil type of winding which, as shown before, cannot give the maximum three-phase rating unless six terminals are used.

It should be noted that the three legs shown in Fig. 13 have the same phase relations as a delta winding when used on single-phase; that is, one of the three legs is in phase with the terminal voltage, while the other two legs have a 60-degree relation. However, these two legs, with the 60-degree relation, carry the full current A; while in the delta arrangement they carry one-half current.

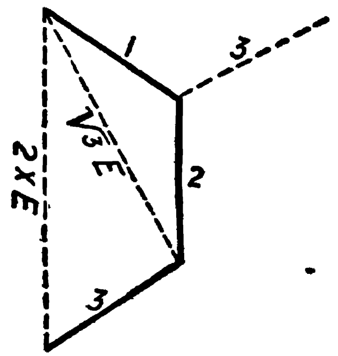


Fig. 13

Therefore, although the voltage relations are the same, the current relations are quite different; which accounts for the increased capacity with the groups connected as in Fig. 13 or Fig. 12.

Fig. 13, like Fig. 12, is equivalent to covering the entire armature surface with copper which is equally active in carrying current when the machine is operated single-phase. However, compared with the three-phase star arrangement where two legs only are active, it may be seen that the voltage and the output have been increased in the ratio of 100: 86.6, or about 15 percent, by the addition of 33 1-3 percent in copper, and 33 1-3 percent in total armature copper loss. It is evident, therefore, that the addition of a third leg when operating single-phase does not give results in proportion to the material used.

Comparison of Single-Phase and Three-Phase Ratings on the Basis of Equal Total Armature Copper Loss

All the foregoing comparisons have been on the basis of equal losses in a given coil or group; but it has been shown that with some of the windings, when operated on single-phase, the currents are not divided equally. In consequence, in such cases the total copper loss in the windings must be less than where the current is divided equally. In the following comparisons the total copper losses for three-phase and single-phase are given, and the possible increase in single-phase rating for the same total copper loss is indicated

Let r = the resistance of one group.

Let A = the limiting current per group, which has been used in the above comparisons.

Then in Fig 3, for three-phase, $6A^2r$ = the armature copper loss. For single-phase $\left(\frac{A}{2}\right)^2 \times 4r + 2A^2r = 3A^2r$ = total armature copper loss.

The three-phase loss is therefore twice the single-phase on the basis of equal limiting current For equal total loss the single-phase current could therefore be increased as the $\sqrt{2}$, as the loss varies as the square of the current. As the former single-phase output was 50 percent of the three-phase, then for equal losses the single-phase output becomes $50 \times \sqrt{2} = 70.7$ percent of the corresponding polyphase rating.

In Fig. 5, the three-phase loss $= 6A^2r$. The single-phase loss with the same limiting current $= 4A^2r$, as there are but four legs in circuit instead of six, each leg carrying the same current as when operating three-phase. The three-phase loss is thus 6/4 single-phase, and for equal losses the single-phase current can be increased in the ratio of $\sqrt{6/4}$. The former single-phase rating was 57.7 percent. This therefore can be increased to $57.7 \times \sqrt{6/4} =$ 70.7 percent of the corresponding three-phase rating.

In Figs. 7 and 8, the three-phase loss $= 6A^2r$. The single-phase loss $= 3A^2r$, as determined by direct inspection of currents and resistances. For equal losses, therefore, the single-phase current can be increased as the $\sqrt{2}$. The output then becomes $50 \times \sqrt{2}$ = 70.7 percent of the corresponding three-phase rating.

In Figs. 9 and 10, the three-phase loss $= 6A^2r$. Single-phase loss $= 4A^2r$. The single-phase output = 57 7 percent and for

equal loss this can be increased in the ratio of $\sqrt{6/4}$. The output then becomes 70.7 percent of the corresponding three-phase output.

In Fig. 12, the six-phase loss $= 6A^2r$. The single-phase loss $= 6A^2r$, as all the groups carry equal currents and all are in circuit. Therefore the single-phase current cannot be further increased and the single-phase output remains at 66.7 percent of the six-phase output (or three-phase beyond the transformers.)

From this it would appear that most of the above windings would give, for equal armature copper loss, 70.7 percent of the three-phase rating. However, it should be taken into account that the three-phase ratings are not all equal on the basis of equal copper loss.

In Figs. 3 and 5, for instance, the three-phase ratings are equal to 5.196 AE. The three-phase ratings with the arrangement shown in Figs. 7, 8, 9 and 10, are equal to $6AE$. Therefore Figs. 3 and 5 have only 86.6 percent of the three-phase ratings of 7, 8, 9 and 10. The single-phase ratings of Figs. 3 and 5 therefore are 70.7 percent of 86.6 percent, or 61.2 percent of the best three-phase rating which can be obtained. Therefore, on the basis of $6AE$ being the best three-phase output, then with equal copper loss, the arrangements in Figs. 3 and 5 give $61.2 \times 6AE = 3.792AE$ as the single-phase rating with equal copper loss, while Figs. 7, 8, 9 and 10 give 4 243AE as the single-phase ratings with equal copper loss, and Fig. 12 gives $4AE$ as the single-phase rating with the same copper loss. Therefore, the arrangements in Figs. 7, 8, 9 and 10 are better than any of the others for single-phase rating, if total copper loss is the limit rather than the loss in an individual coil or group.

However, if total copper loss is the limit, then there is still a difference between the true delta and star windings. With the delta winding the current A is increased 41 percent, which means that one of the groups will have double the copper loss which it has on three-phase, while with the star winding the current A will be increased slightly over 22 percent, which means that two groups of the winding will have their copper losses increased 50 percent. The star arrangement, even with the same total copper loss, works the individual coils on single-phase easier than in the delta arrangement.

The following table summarizes the above relationships.

Type of Winding	E.M.F. Across Terminals		Capacity, with Limiting Amperes A, per Coil				Armature Copper Loss with Amps. A Resist r per Group		Armature Copper Loss, 1-Phase and 3-Phase Equal			
	3-Ph.	1-Ph	3-Ph.	1-Ph.	Ratio 1-Ph to Cor'd'g 3-Ph	Ratio 1-Ph to Best 3-Ph	3-Ph	1-Ph	Amperes A_1	Capacity with Amperes A_1	Increase in Cop'er Loss in Coils Carrying Current A_1	Ratio 1-Ph Capacity Best 3-Ph.
Fig 3	$\sqrt{3}$ E =1 732E	1 732E	3Ax$\sqrt{3}$ E =5 192AE	1.5Ax$\sqrt{3}$ E =2 596AE	50%	43 3%	$6A^2r$	$3A^2r$	$\sqrt{2}$ A =1.414A	$\sqrt{2}$ x 1 5 $\sqrt{3}$AE =3 675AE	100%	61.2%
Fig 5	3E	3E	$\sqrt{3}$ A x 3E =5.192AE	Ax2E =3AE	57.7%	50%	$6A^2r$	$4A^2r$	$\sqrt{6/4}$ A =1 225A	1 225x3AE =3 675AE	50%	61 2%
Fig 7 and 8	E 2E	E 2E	2Ax3xE =6AE Ax3x2E =6AE	1.5x2AxE =3AE 1.5xAx2E =3AE	50%	50%	$6A^2r$	$3A^2r$	$\sqrt{2}$ A =1.414A	$\sqrt{2}$ x 3AE =4 242AE	100%	70 7%
Fig. 9 and 10	$\sqrt{3}$ E =1 732E 2 $\sqrt{3}$ E =3.464E	1.732E 3 464E	2 $\sqrt{3}$Ax$\sqrt{3}$ E =6AE $\sqrt{3}$Ax2 $\sqrt{3}$ E =6AE	2Ax$\sqrt{3}$ E =3.464AE Ax2 $\sqrt{3}$ E =3.464AE	57.7%	57.7%	$6A^2r$	$4A^2r$	$\sqrt{6/4}$ A =1 225A	1 225x$\sqrt{3}$AE =4 242AE	50%	70.7%
Fig 12	2E	2E	6AE	2Ax2E =4AE	66 7%	66.7%	$6A^2r$	$6A^2r$	A	4AE	0	66 7%

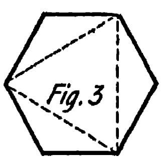


Fig. 3

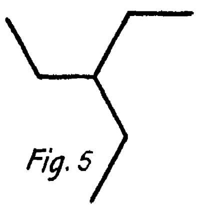


Fig. 5

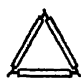


Fig. 7

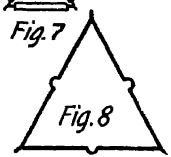


Fig. 8

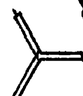


Fig. 9

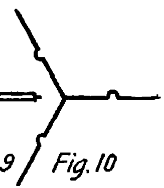


Fig. 10

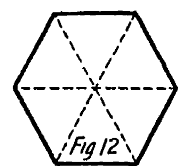


Fig 12

Two-Phase Windings

The two-phase windings may be analyzed in a manner similar to the preceding. Starting with a closed-ring arrangement, just as in the three-phase, the various relations may be readily determined. Assuming a ring, as in Fig. 14, with four taps brought out at 90 degrees apart and assuming that this winding is the same in every way as that in Fig. 1, then the following e. m. f.'s and capacities are obtained.

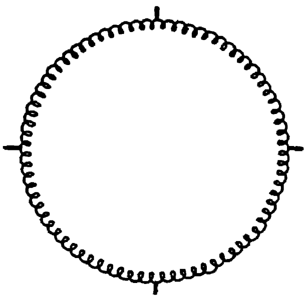


Fig. 14

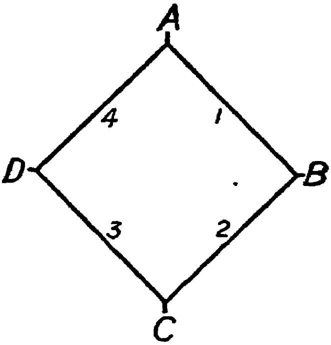


Fig. 15

Fig. 15 represents a closed coil two-phase winding corresponding to the three-phase winding in Fig. 3. Calling E the e. m. f. of the groups of legs, then the e. m. f.'s AC and $BD = \sqrt{2} \times E$.

Opening Fig. 15 at two opposite points as in Fig. 16, the two parts may be rearranged to give Fig. 17. This is an interconnected open coil two-phase winding; that is, the central points are connected together so that there are fixed e. m. f. relations between all four terminals. The e. m. f. Ad is equal to E, and the e. m. f. across AB, BC, etc. $= \sqrt{2} \times E_1$, while the e. m. f. across AC and $BD = \sqrt{2} \times E_1$.

Splitting the winding of Fig. 16 at four points, then the arrangements shown in Figs. 18 and 19 are obtained. These two windings are equivalent, except that in Fig. 18 the two legs which are in phase are connected in parallel, while in Fig. 19 they are in series. If the middle points in Fig. 19 are connected together the arrangement becomes equivalent to Fig. 17. In Fig. 18, e. m. f.'s AC and BD are equal to E_1, while there is no fixed e. m. f. relation between AB, BC, etc.

In Fig. 19 the e. m. f.'s AC and BD are equal to $2E_1$ and there is no fixed relation between AB, BC, etc., unless the middle points

are interconnected, in which case the e.m.f.'s become the same as in Fig. 17.

In Figs. 20 and 21 the usual two-phase, three-wire arrangement is shown. In Fig. 20, $AB = E_1$ and $AC = \sqrt{2} \times E_1$. In Fig. 21 $AB = 2E_1$ and $AC = 2 \times \sqrt{2}\, E_1$.

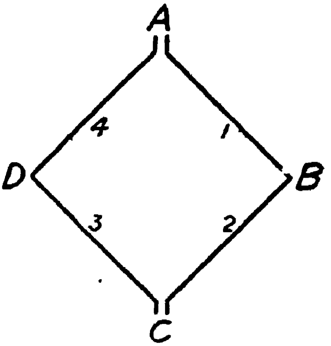


Fig. 16

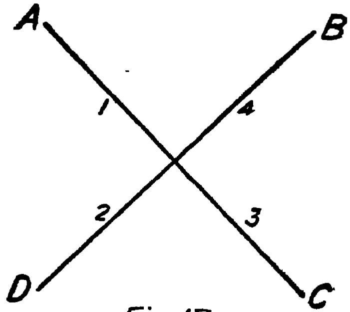


Fig. 17

CAPACITIES OF TWO-PHASE WINDINGS: Let A equal the current per coil, this current being the same as for the three-phase winding. Then—

In Fig.	15	the capacity	equals	4 AE_1
" "	17	"	"	4 AE_1
" "	18	"	"	4 AE_1
" "	19	"	"	4 AE_1
" "	20	"	"	4 AE_1
" "	21	"	"	4 AE_1

It is obvious therefore that the two-phase capacities are equal for all the various windings which have been commonly used.

COMPARISON OF TWO-PHASE CAPACITIES WITH THREE-PHASE

As the same winding has been assumed for both two-phase and three-phase, it is of interest to compare their ratings. Comparing E and E_1 in Fig. 22, it may be seen that $E_1 = \sqrt{2} \times E$. Therefore the two-phase capacities given above, when put in terms of three-phase e.m.f.'s become, in all cases, $4A \times \sqrt{2} \times E = 5.656\ AE$. The closed coil three-phase capacity $= 5\ 196\ AE$. The closed coil six-phase capacity $= 6\ AE$. The open coil (star or delta) three-phase capacity $= 6\ AE$. Therefore, the three-phase closed coil arrangement gives the least output, while the two-phase, (which is

in reality, four-phase with a closed coil winding) gives somewhat better results and the six-phase closed coil gives still better results.

Single-Phase Rating from Two-Phase Winding

Two of the terminals of the two-phase windings may be used for single-phase. Assuming the same current A per coil as in

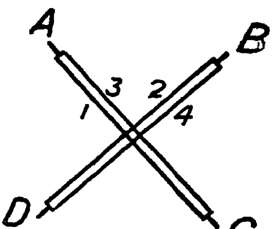


Fig. 18

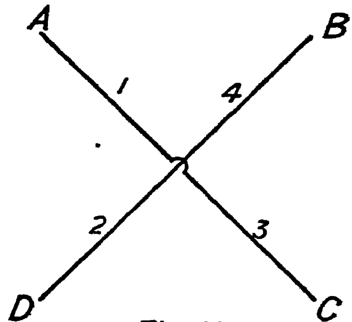


Fig. 19

two-phase or three-phase, then the single-phase capacity becomes

In Fig. 15 $= 2A \times \sqrt{2}\,E_1 = 2.828\,AE_1$

In Fig. 17 $= A \times 2E_1 = 2\,AE_1$

In Figs 18 and 19 $= 2\,AE_1$

In Figs 20 and 21 $= 2\;828\,AE_1$

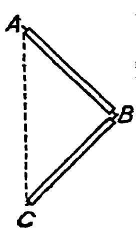


Fig. 20

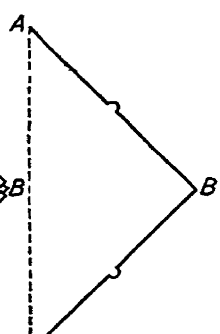


Fig. 21

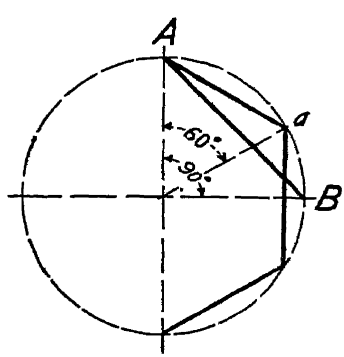


Fig. 22

Comparing the best single-phase obtained from the two-phase with the best single-phase from the three-phase windings, E_1 being equal to $\sqrt{2}\,E$, the following is obtained·

Then 2.828 $E_1A = 4\ AE$, or same as obtained from the six-phase closed coil winding.

Comparing the three-phase closed coil winding with the two-phase closed coil winding for both polyphase and single-phase ratings, the following is obtained on the basis of same loss per coil:

The 3-phase closed coil winding gives 3-phase rating of 5 196 AE.
" 3 " " " " " single" " " 2.596
" 2 " " " " " 2 " " " 5.656 AE
" 2 " " " " " single" " " 4 AE.

It is therefore apparent that with the closed coil winding the two-phase arrangement (or four-phase in reality) gives higher outputs, for both polyphase and single-phase, than the three-phase closed coil arrangement will give.

It may be of interest to note that in the earlier Westinghouse polyphase machines, when the single-phase rating of a polyphase generator was frequently of more importance than the polyphase rating, the closed coil two-phase winding shown above was generally used. One reason for the selection of this type of winding was the high single-phase rating which could be obtained without undue sacrifice in the polyphase rating.

Special Connections for Single-Phase

All of the preceding comparisons have had to do with symmetrical arrangement of windings. However, by putting on one or more additional connections, which are used for single-phase operation purely, the windings can sometimes be made to give larger single-phase ratings than where the straight polyphase connections are used for single-phase operation. Two such arrangements will be shown below:—

It is shown in Fig. 12 that by taking off single-phase at Ab, a high single-phase rating can be obtained. For supplying three-phase circuits, however, it was stated that transformers would have to be interposed to transform from six-phase to three-phase. However, by using A and b as the single-phase terminals and using A, B and C as the three-phase terminals, thus having four terminals total on the winding, as shown in Fig. 23, the machine can supply three-phase directly to the circuit and can also deliver single-phase with the best utilization of winding. In this case the three-phase rating equals 5.196 AE and the single-phase rating equals 4 AE. The single-phase thus becomes approximately 77 percent of the polyphase. This high relative rating, however,

is due to the fact that the three-phase rating is only 86.6 percent of the maximum three-phase which could be obtained.

In a similar way, with the delta winding shown in Fig. 8, an improved single-phase rating can be obtained by putting an additional terminal at the middle of one of the legs, as shown in Fig. 24. The single-phase is then taken off at A and b, while A, B and C are the three-phase terminals. In this case two of the delta legs are almost in phase with the single-phase, while the third leg is practically idle as far as voltage is concerned, although it carries the full current. If the e. m. f. of AB is $2E$ then the e. m f. of AB is $\sqrt{3}\ E$. The total single-phase current is $2A$. Therefore, the

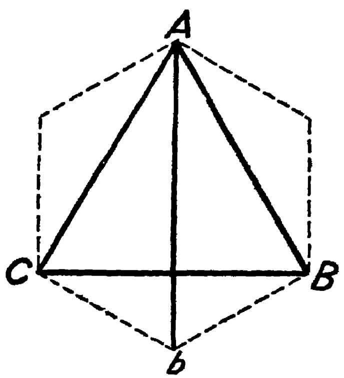


Fig. 23

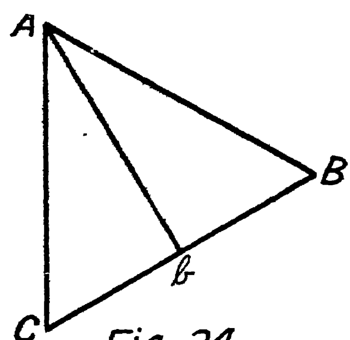


Fig. 24

single-phase rating becomes 3.464 AE. The single-phase rating in this case is therefore 57.7 percent of the three-phase, instead of 50 percent where the single-phase was taken off at the terminals AB.

The above two arrangements are therefore more effective than the usual single-phase from the same types of windings. However, as will be shown later, the true delta and the closed coil three-phase windings are seldom used on alternating-current generators and therefore the above special arrangements are of no particular commercial advantage.

Comparison of Alternating and Direct-Current Ratings From Same Armature Winding

If direct current be taken from the same winding as described, the limiting current per coil should be the same as the effective (or square root mean square) current when delivering alternating

current. This is the value A used in the preceding comparisons. The direct-current e. m. f. is taken off from two opposite points of the armature. This e. m. f. therefore corresponds to the two opposite terminals of either the two-phase closed coil or six-phase closed coil winding shown in the preceding diagrams. The direct-current e. m. f. will be equal to the maximum or peak value of the alternating-current e. m f. taken off from these two points This will be $\sqrt{2}$ times the effective value used in the preceding comparison.

For the six-phase diametral arrangement, it was shown that the effective alternating-current e m. f. = $2E$. Therefore the peak value of direct-current e. m. f. will be equal to $\sqrt{2}$ x $2E$. As the limiting current is A, and as there are two direct-current branches, the total direct current will be $2E$. The direct-current output therefore becomes 4 x $\sqrt{2}$ AE = 5.656 AE.

The following interesting comparisons can therefore be made:

Direct-current capacity	=5 656 AE	
1-Phase closed coil capacity	=4 AE	=70.7% of D C.
3-Phase " " "	=5.192 AE	=91 8% " "
2 " (4-phase) " "	=5 656 AE	=100% " "
6 " " " "	=6 AE	=106 1% " "
3 " open " "	=6 AE	=106 1% " "

From the above it appears that the two-phase closed coil (and two-phase open coil) capacity is equal to the direct-current capacity from the same armature winding. The three-phase closed coil is less than the direct current, while the six-phase is greater than the direct current. The three-phase true star or delta winding and the six-phase closed coil winding are all slightly more effective than when the same winding is used for direct-current.

The question may be raised whether still higher ratings could not be obtained from a given winding by taking off more phases. An examination will show that higher ratings can be obtained with the number of phases increased, with the closed coil winding; but it can be shown that the possible increase over the six-phase arrangement is very small.

An easy way of comparing the ratings of closed coil windings, with different numbers of phases, is to compare the number of circuits which can be taken off between adjacent taps or terminals all around the winding, as referred to in first paragraph of page 120. This is equivalent to comparing the perimeters of the poly-

gonal figures shown in the diagrams for the various closed coil combinations and is illustrated in Figs. 25, 26, 27 and 28.

In Fig. 25, calling one side E, than the perimeter $= 6E$

In Fig. 26, the perimeter $= 5.656\ E$. In Fig 27 the perimeter $= 3\sqrt{3}\ E = 5.196\ E$. In Fig. 28, which represents single-phase, the two sides of the polygon coincide, making a straight line Therefore, double the length of this line should represent the perimeter, which $= 4E$. A comparison of these values shows that they are exactly in proportion to the alternating-current capacities given above

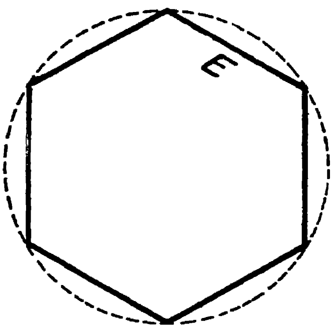


Fig. 25

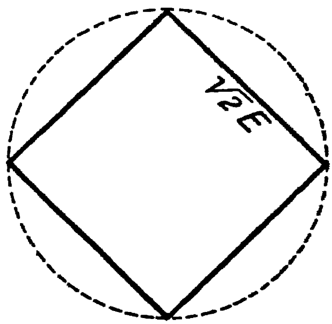


Fig. 26

It is evident that the greater the number of phases obtained from the closed coil winding, the more nearly the perimeter of the polygon approaches the circumference of the circle. With an infinite number of phases a true circle would be obtained and in this case the perimeter becomes $2\pi E = 6\ 283\ E$. Therefore, the maximum possible polyphase rating is $\frac{6\ 283}{6.0} = 1.047$, or 4.7 percent greater than the six-phase closed coil rating or the true star and delta rating. Also, the greatest possible polyphase rating is greater than the direct-current rating in the proportion of 6.283: 5.656, or approximately 11 per cent.

Field Heating

In the above comparisons of the relative ratings of the three-phase, two-phase and single-phase windings, only the armature copper losses have been taken into account: but if the problem is to be considered in its completeness, other armature conditions and the field conditions must also be taken into account.

A comparison of the three-phase and two-phase ratings shows that they are usually so close together that the field conditions would probably not exert a controlling influence on the relative capacities In general, it may be taken that those combinations of polyphase windings which give lower ratings at the same time give lower armature reactions.

In comparing single-phase with polyphase ratings, however, the field conditions, both as regards the field winding and field core, must be taken into account The armature reaction of the single-phase winding is pulsating and tends to produce magnetic disturb-

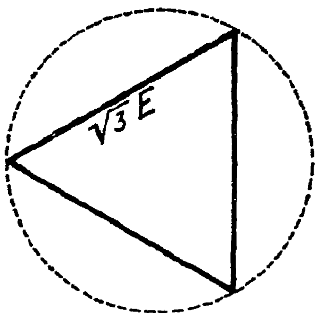


Fig. 27

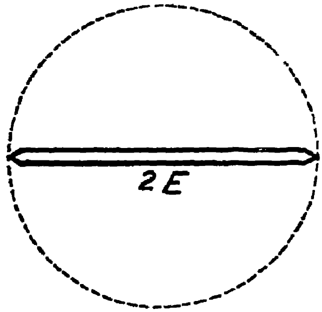


Fig. 28

ances in the field poles or core which may result in very considerable iron losses, both eddy and hysteretic. In general, these disturbances are relatively much greater on larger capacity machines, so that provision must be made on such machines for suppressing or avoiding the ill effects of the armature reaction. This can be accomplished to some extent, by completely laminating the field poles. Another method which has been used on very large machines is the employment of heavy cage damper in the pole faces, similar to that of the secondary of an induction motor. This damper must have current capacity such that when developing ampere turns sufficient to completely neutralize the armature pulsations, the heating effect in the damper winding, due to the current in it, is relatively low.

Field copper heating, in most cases, is not a controlling condition, owing to the fact that the single-phase rating, defined by the armature heating, as indicated above, is so much lower than the polyphase rating that the field copper is usually worked somewhat easier than on the polyphase loading. This is particularly

true when the rating is fixed by the heating of individual armature coils. However, if the single-phase rating is determined by the total armature loss and not by the loss in individual coils, then the permissible armature capacity on single-phase may be such that in some instances the field copper is worked harder than on polyphase. In such cases, if the field copper is the limiting condition, then the single-phase rating cannot be as high as the armature would permit. It may be assumed, however, that in large machines the armature conditions, as fixed by the loss in individual coils, determine the safe single-phase rating; and under this assumption the field conditions, except in regard to the use of dampers or the elimination of the effects of armature reaction, need not be considered.

Application of Various Types of Alternating-Current Windings

The three-phase true star type of winding is the one which, in general, lends itself to best advantage to the various types of alternating-current machinery. It may be a question then as to why any other types of windings are used. However, it was intimated before that where other than the true star winding is used, there is usually some condition other than the output which is of first importance. In the following will be given some of the principal applications of the different types of windings:—

Closed Coil Types

The closed coil type of winding is always used with rotary converters. The controlling feature in this case is that the rotary converter carries a commutator, which naturally requires a closed coil type of winding. Rotary converters are, in practice, wound for three-phase as in Fig. 3, four-phase (usually called two-phase) as in Fig. 15 and six-phase as in Figs. 11 and 12; and the number of collector rings is 3, 4 and 6 respectively. The three-phase winding is generally used in small capacity rotaries. While the three-phase winding allows less output than the four-phase or six-phase, on small rotaries the capacity is usually not limited by the armature copper loss, while the use of three rings somewhat simplifies the machines.

Four-phase rotaries are used to a very considerable extent in connection with two-phase circuits. However, where the supply

circuit is three-phase it is rare that the transformation is from three-phase on the supply circuit to the two-phase on the rotary, as there are certain disadvantages in such transformation which more than offset the slight advantage of the four-phase rotary over the three-phase Moreover, where a higher number of phases is of advantage in a rotary converter, it is practicable to transform from the three-phase supply circuit to six-phase for the rotary Two arrangements of such six-phase transformation are in use, as illustrated in Figs 11 and 12

One of these is the so-called "Double Delta" arrangement, in which each of the step-down transformer circuits is equipped with two secondaries, as indicated in Fig 11 These are connected to form two separate deltas, one being inverted with respect to the other.

The other arrangement is the so-called "Diametral" arrangement, as shown in Fig 12 This has advantages over the double delta in that only one secondary circuit is required for each phase and the middle points of these secondary circuits may be connected together for a neutral or middle wire between the direct-current leads from the rotary converter.

In a rotary converter the armature copper loss is generally so small, compared with that of the straight direct-current or straight alternating-current machine with the same winding, that all considerations of the comparative heating of three-phase, four-phase and six-phase windings, as on alternating-current generators, has practically no bearing on the rotary converter rating. In a rotary converter, an increase in the number of phases over six represents a considerable reduction in the armature copper loss,—much more so than in the closed coil alternating-current generator This is due, in the rotary converter, to the fact that one armature winding carries both the direct and the alternating currents, which are to a certain extent, flowing oppositely.

Closed coil windings are also occasionally used on the secondaries of induction motors in order to give a better choice in the number of slots than would be allowed otherwise Such windings when used on induction motors are usually of the two-circuit or series type, for the purpose of increasing the voltage as much as possible and at the same time keeping the number of conductors as small as possible, while retaining the closed coil arrangement. A two-circuit closed coil winding will close upon itself symmetrically if the number of turns or coils is one more or less than a multiple

of the number of pairs of poles. This sometimes allows the use in the secondary of an induction motor, of a number of coils or slots which has no close numerical relation to the number of primary slots. For instance, if the primary of a four-pole induction motor has 48 slots with an open coil, star or delta winding, then with 39 coils and slots in the secondary, a symmetrical closed coil three-phase winding could be obtained, while if an open coil secondary were used, the number of slots should preferably be 36 or 42, which might not be as desirable as 39 in some cases. This simply illustrates an occasional use of the closed coil winding.

Closed coil windings were at one time used very extensively on low voltage, rotating armature, two-phase generators. Such generators were very satisfactory for delivering a relatively large percentage of their rating as single-phase. Furthermore, with one conductor per slot and with bolted-on end connectors, the potential between adjacent end connectors was at all points relatively low. The symmetrical arrangement of such windings also rendered them very suitable for use with supporting bands or end bells over the end winding. However, with the advent of the rotating field machines, and particularly with the use of higher voltages, the open coil star winding has entirely superseded the closed coil type of generator winding.

THREE-PHASE STAR WINDINGS

Two types of star windings have been shown, namely, those in Figs. 5 and 10. That of Fig. 5 gives less output than that of Fig. 10 in the ratio of 86 6: 100. There would appear therefore to be no use for the Fig. 5 arrangement; but, in certain cases, in using a given winding it may be desired to reduce the voltage from 12 percent to 15 percent while retaining normal conditions otherwise. In such a case the lower voltage could be obtained, if a new winding were used, by simply chording the winding one-third the pitch. On the other hand, if an existing winding is to be used, the same result could be obtained by coupling as in Fig. 5.

In induction motors the arrangement shown in Fig. 5 may be used occasionally where the windings are arranged for coupling for two different speeds. In some cases this type of winding may give better average field distribution for the two numbers of poles than the one shown in Fig. 10. In this case therefore it is the distribution of the magnetic field, and not the capacity of the winding, which is the important feature.

The arrangement shown in Fig. 10 is the true star winding which is used almost universally on three-phase machines. For a given voltage it requires fewer conductors than any other type of winding. This is of very material advantage in allowing, with a given number of slots, a smaller number of conductors per slot, which, as a rule, allows a better utilization of the star space:—That is, more copper can be gotten into a given slot. Furthermore, in relatively high voltage machines where the conductors may be very large in number and small in size, the star winding with its smaller number of conductors, each of much larger size, gives more substantial coils than any other arrangement. Another advantage of the three-phase winding is its fairly good utilization of copper when operated on single-phase. When operated on purely single-phase load, one leg of the star could, of course, be omitted, but if it is retained it becomes a reserve winding which may be used in case of an accident to one of the active legs of the winding By opening any defective coils in an active leg and connecting in the reserve leg in place of the defective one, the machine can still develop its specified rating on single-phase.

Another advantage of the star type of winding is the readiness with which the central or neutral point can be grounded, which is a very considerable advantage in some high voltage systems.

Delta Type Windings

The true delta type winding, as illustrated in Figs. 7 and 8, is not used to any great extent in either alternating-current generators or induction motors. For a given voltage it requires 73 percent more conductors, each of 58 percent of the capacity of those of the true star type of winding. As the terminals of all three legs are connected in a closed circuit it is necessary that the e. m. f.'s generated in the three legs should balance each other at all instants or there is liable to be circulating current around the windings. This means that the winding must be applied only where the conditions are favorable, or the conditions in the design must be made to suit the type of winding. This winding is occasionally used on low voltage turbo generators of fairly large capacity, due to the fact that the delta type winding requires more conductors than the star type. For example, in a large capacity two-pole turbo-generator, wound for relatively low voltage, the number of conductors for the star winding may be so small that a satisfactory number of slots is not obtained, even with only one conductor per

slot and even using the double-star winding, shown in Fig. 9. In such case a double delta winding will allow 73 percent more conductors and slots than the double star will give. Also, each conductor will be much smaller than in the star arrangement, which may be of considerable advantage in the case of low voltages and very heavy current per conductor.

Delta windings are occasionally used on machines which are arranged for connection for two different voltages, such as 6600 volts and 11,000 volts. If an armature is wound for star connection at 11,000 volts, then it can be coupled in delta for 6600 volts with practically the same inductions, losses, field currents, etc. The delta type of winding is also used occasionally in the primaries of induction motors for special purposes, such as multi-speed combinations where the winding is changed from one number of poles to another. In general, however, the star type winding is used on induction motors.

The delta winding is not well adapted for single-phase operation on account of its low capacity. Also, it does not admit of grounding of the neutral or central point of the system. Taking everything into account, the true delta winding is only used where some special condition is imposed upon the winding which puts the star arrangement at a disadvantage.

Single-Phase Alternators

All the foregoing comparisons have been made on the basis of the same armature winding being used for three-phase, two-phase or single-phase The relations shown do not hold true in general for machines which are wound initially for single-phase service, such as for single-phase railway or electro-chemical or electro-fusion work. In such cases the amount of armature copper used and its distribution are such that the armature coils, either individually or as a whole, do not determine the true limits of output; but the armature as a rule can carry anything that the field winding will stand, so that the field temperature becomes the true limit in such machines. Also, very massive, well distributed cage dampers are used with such machines when they are of large capacity and these, in turn, have a certain effect on the characteristics, such as the regulation, and thus have an indirect influence on the permissible capacity. It is well known that if the inherent regulation of an alternator is made poorer, the capacity can usually be increased with the same limiting field temperature. In large single-phase gener-

ators, especially for railway service, the capacity is increased by sacrifice in the inherent regulation of the machine. However, the massive dampers greatly improve the regulation for quick changes in load; while the poorer inherent regulation only affects the regulation over considerable intervals of time, and automatic regulators, acting on the alternator excitation, readily take care of the slow fluctuations. In consequence, single-phase generators of large capacities may be built for ratings which bear no definite relation to any of those given above.

The armature windings of single-phase generators, when arranged for single-phase purely, are frequently distributed over only part of the surface. Usually they cover considerably more than half the surface, and in extreme cases they cover 80 percent or more. Of course, when spaced like a true three-phase winding they cover two-thirds the surface. This arrangement admits of an extra leg being added to the winding, which is normally idle, if the winding is connected in star, this leg being a reserve in case of accident, as mentioned before. However, when such a leg is not added, the winding generally covers more than two-thirds the surface, rather than less, but rarely covers the whole surface.

DAMPERS ON LARGE SINGLE-PHASE GENERATORS

FOREWORD—This formed part of the discussion of a paper presented before the Institute of Electrical Engineers, December, 1908, by Mr. Murray, describing the operation of the New Haven single-phase railway. The effect of the addition of the massive dampers on the rotors of the New Haven generators was so pronounced, and the results were so beneficial, as a whole, that it was considered advisable to publish it as new and interesting material, in the form of a discussion of Mr. Murray's paper. Immediately after the publication of this, heavy dampers were adopted very generally by manufacturers of large single-phase generators, throughout the world, who had encountered more or less trouble of the same nature as found in the New Haven generators. Practically all large single-phase generators since then have been built with such dampers as part of their construction.—(ED.)

WHEN the New Haven single-phase generators were put on load test, the first, and most pronounced, difficulty was in heating, not in the winding, but in the field or rotor structure, due to the pulsating reaction of the armature winding when carrying a heavy load in single-phase current. This reaction was known previously to building these machines, but on machines of smaller capacity it had not developed destructive tendencies. It was proved later that this was simply because it had not been tried out under the conditions which would develop its most harmful effects. This pulsating armature reaction may be analyzed in the following manner:

Consider the armature winding as a magnetizing coil fixed in space and carrying an alternating current. This coil may be considered as setting up an alternating field fixed in space. For analysis, this alternating-current field, fixed in space, may be considered as made up of two constant fields of half value, rotating in opposite directions at the synchronous speed of the machine. One of these fields therefore rotates at the same speed and in the same direction as the rotor. The other field is traveling round the rotor core in the direction opposite to its rotation. This field may therefore be considered as equivalent to one fixed in space with the rotor running in it at double speed. This core thus becomes an armature core subject to a heavy induction at a high frequency.

When the first rotor was built, the structure was laminated as completely as mechanical conditions would permit. However, in the case of high-speed turbine-generators of very large capacity, it is almost impossible completely to laminate everything, due to the fact that the mechanical requirements call for rigidity in some of the structural features. Upon testing the first machine it was found that there was local heating, with heavy load, sufficient to create hot spots in the core; and in a comparatively short time in turn these hot spots damaged the insulation on the coils from the outside, thus causing grounds on the winding. As soon as this was noticed, an effort was made to eliminate these hot spots; but it was found, after several attempts, that as soon as one was eliminated others would show up in some different place as soon as a higher load condition was reached. It was evident, after considerable work had been done, that the correct remedy was not being applied to this trouble It was then decided to take a bold step by attempting to eliminate all pulsating reactions from the armature by putting a short-circuited winding on the rotor, of such value that a very large current could flow in it with but very little loss. It was the idea to damp out the field in very much the same way that the armature of a polyphase alternator will demagnetize, or kill its magnetic field, if the armature terminals are all short-circuited together. It is known that under this condition the armature current will rise to such a value that the field flux is practically eliminated. In order to maintain this condition indefinitely without overheating, it is only necessary to put enough copper on the armature so that the I^2R losses in it under this condition are within the temperature capacity of the windings. Working on this theory, a complete cage winding was placed on one of the rotors of the New Haven generators. This rotor had not been designed originally for this purpose, and it was therefore difficult to adopt the most suitable proportions in this winding, but what was put on, immediately showed in practice that a practicable remedy had been applied for this trouble Meanwhile the new rotors designed for the application of heavy cage windings were under construction, and upon the installation of these, the field or rotor trouble all disappeared. It is interesting to note that the fourth machine installed, which has a 4260 kilovolt-ampere single-phase rating, has a solid steel core, in the surface of which the copper cage winding is embedded. As this winding completely eliminated the pulsating armature reaction, there was no further

occasion for laminating the field as a protection from magnetic pulsations.

I might add that a number of the earlier tests, leading up to the design of the first New Haven rotors, were misleading, in the fact that turbine-generators were used for obtaining the preliminary data for single-phase operation and, in all cases, the machines had solid steel cores. These cores acted as dampers to a certain extent, and this in itself eliminated part of the pulsation. It thus developed afterwards, that in the very act of lamination to avoid the trouble, we had gotten into it deeper.

Practically all this work on the generators was done before the full electric service was established, and while only one or two generators were required to be operated at one time. With one generator running, there was apparently but little or no disturbance due to short-circuits on the system. As the service was increased and two generators put in operation, the effect of short-circuits became more pronounced. When, in June, 1908, the entire electric service was established, and three generators were connected to the system, it soon became evident that there was some serious condition existing in the system, as indicated by the extremely violent shocks to everything in case of a short-circuit. This was particularly noticeable in the switching system, and, as Mr. Murray intimates, in the case of a short-circuit, all the switches in the system felt it their duty to jump in and open the circuit. This indicated an abnormal current condition. It was calculated that these machines would give possibly six or seven times full-load current on the first rush, in the case of a dead short-circuit, this excess current dying down to possibly two or three times normal full-load current. All indications were, however, that this current was being greatly exceeded, and therefore a series of oscillograph tests were made to determine the current rush when the lines were purposely short-circuited under various conditions. These tests indicated that under certain conditions each machine could give, at the moment of short-circuit, almost 5000 amperes on one phase, the normal full-load current being 340. With three machines in parallel, this would therefore mean that approximately 15,000 amperes could be delivered momentarily. This enormous current rush was sufficient to explain many of the difficulties, but this was not all the explanation. The oscillograph tests also showed that this short-circuit current would be maintained at almost its maximum value for a very considerable

period, due to the cage winding on the rotors of the generators. Apparently this current at the first rush, was not appreciably greater than that on the machine before the dampers were added, but without the dampers the field was killed more quickly by this enormous current, so quickly that apparently the breakers did not open until the current had fallen somewhat. However, with the heavy cage winding on the field structure, secondary currents were set up in this winding, tending to maintain the field strength, and thus the current rush was maintained at almost full value for possibly 20 to 30 alternations. These oscillograph tests indicated very clearly that the armatures of these generators did not have nearly so great internal self-induction as our calculations indicated.

Meanwhile, the generators in the power house had been suffering from the tremendous shocks which accompanied short-circuits on the line. There is necessarily considerable local field around the end-windings of all these machines, and this stray field is especially large on machines with a small number of poles, and, in consequence, high ampere-turns per pole. These stray fields at the ends tend to exert a bending or distorting effect on the end-windings. In any given machine the distorting force varies as the square of the current carried by the coils. Our experience with the windings on these machines indicated that they were being subjected to enormous forces in the end-windings. The oscillograph tests gave an indication as to the amount of this force. As the machines could give about 15 times full-load current momentarily on short-circuit, the force acting on these end-windings would be 225 times normal; in this case, therefore, these forces were so great that it became a serious problem to devise a type of bracing on the end-windings sufficient to withstand such a force. It should also be borne in mind that probably as many short-circuits came, in one day, on these generators, as the ordinary high-voltage power-house generator is called upon to sustain in one year. While ninety-nine shocks out of a hundred might not be sufficient to do damage, yet if the shocks occur frequently enough, the hundredth one will soon be reached. In our endeavors to support these windings against movement, probably the most complete system of bracing ever applied to alternating-current generators was developed and used on these machines.

But in spite of this there was evidence of movement at times. It thus became evident that some method of limiting this short-circuit current to the value originally intended; namely, about

six times full-load current, would have to be applied. This was done by placing an unsaturated choke-coil, or impedance coil, on the trolley side of each machine This coil takes up a comparatively small voltage under normal operation, but in case of a short-circuit, the electromotive force generated in it is sufficient to limit the current rush to less than half the value it would attain without this coil Thus as the shock on the end-windings of the generators varies as the square of the current, it is evident that cutting this current in half would cut the shock to one-quarter of its former value, which, with the method of bracing used on these machines, would mean the difference between good and bad.

When these choke-coils were installed, the results on the power house were evident The shocks on the machines were very greatly reduced, so reduced that we do not fear future trouble from this source. It is interesting to note that No. 4 machine; that is, the 4260 kilovolt-ampere generator, referred to before, was put in service a considerable time before the choke-coils were installed, and it went through the most severe short-circuits ever encountered on this system. Its armature winding has never shown any distress. This is partly because, in the design of this machine, the difficulties to be overcome were known, and the remedies could be applied in the most suitable manner.

An interesting point in connection with the use of the cage windings on these generators, is that the apparent regulation of the system has been improved. This was anticipated, but the actual result in practice was more pronounced than was expected. In installing new rotors for these machines with the heavier cage dampers, the inherent regulation of the generators was made somewhat poorer than before, partly in order to accommodate certain structural features in the rotor. It was anticipated that the cage winding with its damping effect would, to a certain extent, mask this poor regulation by making the machine sluggish as regards fluctuation in voltage with sudden variations in load. In practice it was found that, with the later rotors with their poorer inherent regulation, the average regulation of the system was considerably better than before, thus indicating that most of the disturbances in the voltage, when the old rotors were used, were due to sudden changes in load, while the slow variations were taken care of by the automatic regulators. With the new rotors the voltage changes are so slow, that the Tirrill regulator

has plenty of time to act before any serious disturbance can take place.

It must be borne in mind that in one way this New Haven power-house installation was more difficult than anything undertaken heretofore, and that is, in the use of 11,000 volt generators with one terminal connected directly to ground Taking this condition into account, together with the enormous current rushes with consequent shocks on the winding, and the single-phase operation of units of such large capacity, it may reasonably be claimed that this was the most difficult case of alternating-current generation ever undertaken.

DEVELOPMENT OF A SUCCESSFUL DIRECT-CURRENT 2000 KW UNI-POLAR GENERATOR

FOREWORD—In 1906, the Westinghouse Company contracted to build a 2000 kw uni-polar type generator direct coupled to a 1200, revolution steam turbine. Many difficulties were encountered in shop tests on this machine, which were apparently corrected, but upon installation and operation on the customer's premises, many new and totally unexpected difficulties arose.

This paper illustrates how a responsible manufacturing company will throw its whole engineering and manufacturing endeavors into correcting serious difficulties. It also serves to give student engineers a good idea of the practical side of manufacturing engineering. Fearing the results of the engineering efforts expended on this machine would eventually be lost, the author prepared them for presentation at the twenty-ninth annual convention of the American Institute of Electrical Engineers at Boston, June, 1912.—(ED.)

THIS paper is not intended to be a theoretical discussion of the principles of unipolar machines; neither is it a purely descriptive article. It is a record of engineering experiences obtained, and difficulties overcome, in the practical development of a large machine of the unipolar type. Some of the conditions of operation, with their attendant difficulties, proved to be so unusual that it is believed that a straightforward story of these troubles, and the methods for correcting them, will be of some value.

Two theoretical questions of unipolar design have come up frequently; (1) whether the magnetic flux rotates or travels with respect to the rotor of the stator; and (2) whether it is possible to generate e.m.fs. in two or more conductors in series in such a way that they can be combined in one direction, without the aid of a corresponding number of pairs of collector rings, to give higher e.m.fs. than a single conductor.

To the first question the answer may be made that in the machine in question, it makes no difference whether the flux rotates or is stationary; the result is the same on either assumption. To the second it may be said that when the theory of interlinkages of the electric and magnetic circuits is properly considered, it is obvious that the resultant e.m.f. is always equivalent to that of one effective conductor. It has been proposed in the

past, by means of certain arrangements of liquid conductors in insulating tubes, to add the e m fs of several conductors in series but such a scheme does not appear to be a practical device There-fore, the theoretical considerations being largely eliminated, the author confines himself to the practical side only.

In 1896 the writer designed a small unipolar generator of approximately three volts and 6000 amperes capacity at a speed of 1500 rev. per min. This machine was built for meter testing and the occasion for its design lay in the continued trouble encountered with former machines of the commutator type designed for very heavy currents at low voltages.

The general construction of this early machine is shown in Fig. 1. The rotating part of this machine consisted of a brass casting, cylindrical shaped, with a central web, very similar to a cast metal pulley. The two outer edges of this pulley or ring served as collector rings for collecting the current as indicated in the figure, while the body of the same ring served as the single conductor. The object of this construction of rotor was to obtain a form which could be very quickly renewed in case of rapid wear, as this arrangement would allow a small casting to be made and simply turned up to form a new rotor. However, this renewal feature has not been of very great importance for the rotor of the first machine was replaced only after 12 years' service. This period of course did not represent continuous service, for this particular machine was used for meter testing purposes or where large currents were required only occasionally.

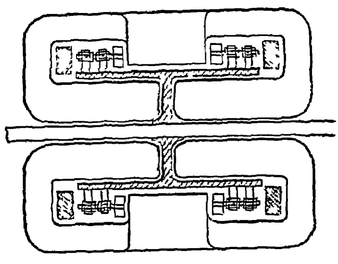


FIG. 1

A number of peculiar conditions were found in this machine. In the initial design the leads for carrying the current away from the brushes were purposely carried part way around the shaft in order to obtain the effect of a series winding by means of the leads themselves. In practice, they were found to act in this manner and, in fact, they over-compounded the machine possibly 30 to 40 per cent. In consequence, it was necessary to shunt them by means of copper shunts around the shaft in the opposite direction.

Shortly after this machine was put in operation there was considerable cutting of the brushes and rings, especially at very heavy currents. It was found that block graphite, used as a lubricant, gave satisfactory results. This machine was operated up to 10,000 to 12,000 amperes for short periods.

The description of the above machine has been gone into rather fully, as it was a forerunner of the 2000-kw. machine which will be described in the following pages. The general principle of construction and the general arrangement of the two parts, or paths, of the magnetic circuit are practically the same in the two machines, as will be shown.

In 1904, due to the rapidly increasing use of steam turbines, the question of building a turbo-generator of the unipolar type was brought up, and an investigation was made by the writer to determine the possibilities. This study indicated that a commercial machine for direct connection to a steam turbine could be constructed, provided a very high peripheral speed was allowable at the collector rings or current collecting surfaces. It appeared that the velocity at such collector surfaces would have to be at least 200 to 250 feet per second, in order to keep the machine down to permissible proportions of the magnetic circuit, and to allow a reasonably high turbine speed. Contrary to the usual idea, the very high speeds obtainable with steam turbines are not advantageous for unipolar machines. For example, while maintaining a given peripheral speed at the current collecting surface, if the revolutions per minute of the rotor are doubled, then the diameter of the rotor collecting rings is halved, and the diameter of the magnetic core surrounded by the collector rings is more than halved, and the effective section of core is reduced to less than one-fourth. The e.m.f. generated per ring or conductor, therefore, on the basis of flux alone, would be reduced to less than one-fourth, but allowing for the doubled revolutions per minute, it becomes practically one-half.

On the other hand, if the revolutions are reduced, while the speed of the collector ring is kept constant, then the e.m.f. per ring can be increased, as the cross section of the magnetic circuit increases rapidly with reduction in the number of revolutions. But at a materially reduced speed, the total material in the magnetic circuit becomes unduly heavy. In consequence, if the speed is reduced too much, then the machine becomes too large and expensive, while with too great an increase in speed,

the e.m.f. per ring becomes low or the peripheral speed of the rings must be very high. It is desirable to keep the number of collector rings as small as possible, for each pair of rings handles the full current of the machine, and therefore any increase in the number of rings means that the full current must be collected a correspondingly large number of times. Therefore, it works out that the range of speeds, within which the unipolar machine becomes commercially practicable, is rather narrow.

In 1906, an order was taken for a 2000-kw. 1200-rev. per min., 260-volt, 7700-ampere unipolar generator to be installed in a portland cement works near Easton, Pa. The fact that it is a cement works should be emphazised, as having a considerable bearing on the history of the operation of this machine, as will be shown later.

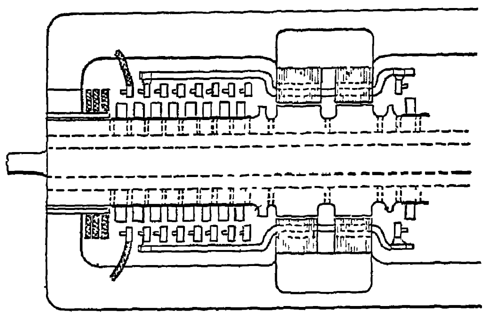


FIG. 2

This 2000-kw. machine does not represent any theoretically radical features, being similar in type to the smaller machine already described, but modified somewhat in arrangement to allow the use of a large number of current paths and collector rings. The general construction of this machine is indicated in Fig. 2.

The stator core and the rotor body are made of solid steel, the stator being cast, while the rotor is a forging. There are eight collector rings at each end of the rotor, the corresponding rings of the two ends being connected together by solid round conductors, there being six conductors per ring, or 48 conductors total. In each conductor is generated a normal e.m.f. of 32.5 volts, and with all the rings connected in series, the total voltage is 260.

The stator core, at what might be called the pole face, is built

up of laminated iron, forming a ring around the rotor. This was laminated in order to furnish an easy method for obtaining the stator slots in which the conductors lie which connect together the brushes or brush holders for throwing the pairs of rings in series. The slots in the stator laminations were made open, as indicated in Fig. 3, in order to readily insert the stator conductors. There are 16 slots in this ring, and in each slot there is placed one large solid conductor.

As first assembled, non-metallic wedges were used to close these slots, but later these were changed to cast iron for reasons which will be explained later.

The rotor core consists of one large forging, as indicated in Fig. 2. Lengthwise of this rotor are 12 holes for ventilating

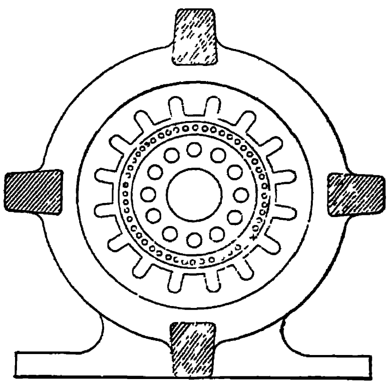


Fig. 3

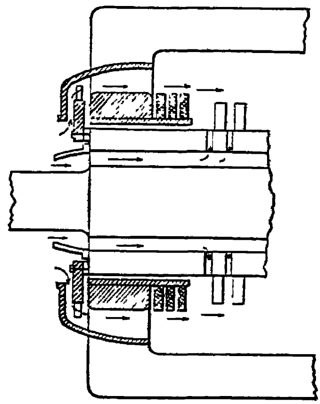


Fig. 4

purposes originally $2\frac{3}{4}$ in. diameter. Each of these holes connected to the external surface by means of nine $1\frac{3}{8}$ in. radial holes at each end of the rotor, these holes corresponding to mid-positions between the collector rings. It was intended to take air in at each end of the rotor and feed it out between the collector rings for cooling. In addition, as originally constructed, there was a large enclosed fan at each end, as indicated in Fig. 4. These fans took air in along the shaft and directed it over the collector rings parallel to the shaft. The object of this was to furnish an extra amount of air for cooling the surfaces of the rings, and the brushes and brush holders, as it was estimated that the brushes and brush holders themselves could conduct away a considerable amount of heat from the rings by direct

contact, and that the cooling air from the fans, circulating among the brush holders, would carry away this heat. These fans were removed during the preliminary tests, for reasons which will be given later.

The rotor collector rings consisted of eight large rings at each end, insulated from the core by sheet mica, and from each other by air spaces between them. Each ring has 48 holes parallel to the shaft. These holes are of slightly larger diameter than

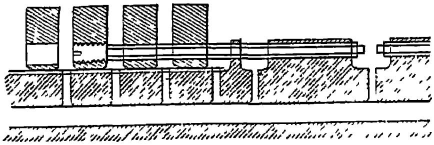


FIG. 5

the rotor conductors outside their insulation. Six holes in each ring were threaded to contain the ends of six of the conductors which were joined to each ring. The six conductors connected to each ring were spaced symmetrically around the core. Fig. 5 shows this construction.

The rotor conductors, 48 in number, consist of one in. copper rods, outside of which is placed an insulating tube of hard material. Each conductor, in fact, consists of two lengths arranged for joining in the middle. The outer end of each conductor is upset to give a diameter larger than the insulating tubes, and a thread is cut on this expanded part. After the rings were installed on the core, the rods were inserted through the holes to the threaded part of a ring and were then screwed home.

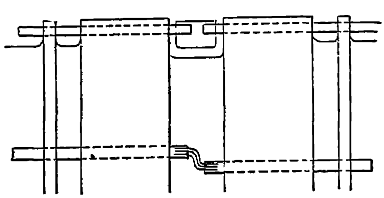


FIG. 6

At the middle part of the rotor core, a groove is cut as shown in Fig. 6. Into this groove the two halves of each conductor project. These two ends are then connected together by strap conductors in such a way as to give flexibility in case of expansion of the conductors lengthwise. This arrangement is also shown in Fig. 6.

With this arrangement there is no possibility whatever of the conductors turning after once being connected. There is

a series of holes from the axial holes through the shaft to this central groove, for the purpose of allowing some ventilating air to flow over the central connections.

As originally constructed, the conductors passed through completely enclosed holes near the surface of the rotor core, as indicated in Fig. 7. This construction was afterwards modified to a certain extent. The face of the rotor at this point was also solid, as originally constructed. This was afterwards changed, as will be described later.

The collector rings, as originally constructed, consisted of a base ring with a wearing ring on the outside, as shown in Fig. 8. Both rings were made of a special bronze, with high elastic limit and ultimate strength. On the preliminary tests these rings showed certain difficulties and required very considerable modifications, and several different designs were developed during the preliminary operation, as will be described.

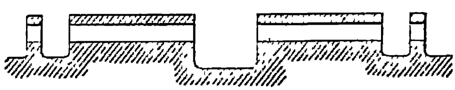


FIG. 7

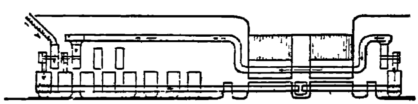


FIG. 9

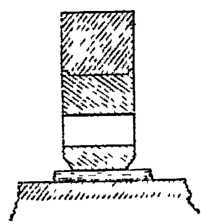


FIG. 8

The eight sets of brush holders at each end are carried by eight copper supporting rings. These supporting rings are insulated from the frame of the machine but are connected in series by means of the conductors through the stator slots. There are 16 brush holders studs per ring and two brush holders per stud, each capable of taking a copper leaf brush $\frac{3}{8}$ in. wide by $1\frac{3}{8}$ in. thick. These brush holders are spaced practically uniformly around the supporting rings. The supporting copper rings are continuous or complete circles, so that the current collected from the brushes are carried in both directions around the ring. There are two conductors carried from each ring through the stator slots to a ring on the opposite side of the machine, in order to connect the various brush holders in series. The arrangement is illustrated in Fig. 9.

The above description represents the machine as originally

constructed and put on shop test. From this point on, the real story begins. Various unexpected troubles developed, each of which required some minor modification in the construction of the machine and, moreover, these troubles occurred in series. that is, each trouble required a certain length of time to develop, and each one was serious enough to require an immediate modification in the machine. In consequence, the machine would be operated until a certain difficulty would develop; that is, that trouble would appear which took the least time to develop. After it was remedied, a continuation of the test would show a second trouble which required a remedy, and so on. Some of these troubles were of a more or less startling nature as will be described later.

This machine, after being assembled according to its original design, was operated over a period of several weeks in the testing room of the manufacturing company. It was operated both at no load and at full load, and a careful study was made of all the phenomena which were in evidence during these tests.

The machine was first run at no-load without field charge to note the ventilation, balance, and general running conditions of the machine. The ventilation seemed to be extremely good, especially that due to the fans on the ends of the shaft. The noise, however, was excessive —so much so that anyone working around the machine had to keep his ears padded. At first it was difficult to locate the exact source of this noise, but it was determined that the end fans were responsible for a considerable part of it.

On taking the saturation curve of the machine, it was found to be extremely sluggish in following any changes in the field current. The reason for this sluggishness is obvious from the construction of the machine, each magnetic circuit of the rotor core being surrounded by eight continuous collector rings of very heavy section, and also by eight brush holder supporting rings of copper of very low resistance. These rings, of course, formed heavy secondaries or dampers which opposed any change in the main flux. The total effective section of these rings was equivalent in resistance to a pure copper ring having a section of 49 sq. in. One can readily imagine that such a ring would be very effective in damping any sudden flux changes. This sluggishness of the machine to changes in flux, however, was not an entirely unexpected result.

The saturation curve showed that the machine could be carried

considerably higher in voltage than originally contemplated, for apparently the magnetic properties of the heavy steel parts were very good, and it was possible to force the inductions in these parts to much higher density than was considered practicable in working out the design. This gave considerable leeway for changes which later were found to be necessary.

In taking the saturation curve, the power for driving the machine was measured and it was found that there were practically no iron losses in the machine; that is, at full voltage at no-load the total measured losses were practically the same as without field charge. This apparently eliminated one possible source of loss which was anticipated, namely, that due to the large open slots in the stator pole face, these slots being very wide compared with the clearance between the stator and rotor

After completion of this test the machine was then run on short circuit Apparently, as there was no iron loss shown in the no-load full voltage condition, the short circuit test with full load current should cover all the losses in the rotor which would be found with full load current at full voltage. Experience afterward proved this assumption to be correct, for in its final form the machine would operate under practically the same condition as regards temperature, etc., at full voltage as it would show at short circuit, carrying the same current. the principal difference being the temperature of the field coil.

It was in this short circuit temperature run that the real troubles with the machine began. The measured losses. when running on short circuit, were somewhat higher than indicated by the resistance between terminals times the square of the current. These extra losses were a function of the load and increased more rapidly with heavy currents. The measured power indicated that these excess losses were principally due to eddy currents. However, the total losses indicated in these preliminary tests, although somewhat higher than calculated, were still within allowable limits, as considerable margin had been allowed in the original proportions to take care of a certain amount of loss. It was therefore considered satisfactory to go ahead with the short circuit tests, and in making these it was the intention to operate long enough to determine the necessary running conditions as regards lubrication, heating, etc.

As mentioned before, the original collector rings of the machine each consisted of a base ring upon which was mounted a secondary or wearing ring, it being the intention to have this latter

ring replaceable after it was down to the lowest permissible thickness, as it would be rather expensive and difficult to replace the base ring which carried the rotor conductors. As the inner ring was shrunk on the core and the outer ring was shrunk on over the base ring, with a very small shrinkage allowance, it was considered that the outer ring was in no danger of loosening on the inner ring, especially as both rings, being of bronze, and in good contact, should heat each other at about the same rate. This assumption, however, was wrong. The machine was put on short circuit load of about 8000 amperes early one evening and an experienced engineer was left in charge of it until about midnight. Up to that time the machine was working perfectly, with no under heating in the rings and no brush trouble. although vaseline lubrication was used. About midnight the engineer left the machine in charge of a night operator, and at about three o'clock in the morning this operator saw the brushes beginning to spark and this very rapidly grew worse, so that in a very few minutes he found it necessary to shut the machine down. An examination then showed that several of the outer rings had shifted sideways on the base ring, as indicated in Fig. 10. One of these rings had even moved into contact with a neighboring ring so as to make a dead short circuit on the machine. It was also noted that all the rings which loosened were on one side of the machine, and that the surfaces of the rings exposed to the brushes were very badly blistered. The brushes also were in bad shape, indicating that there had been excessive burning for a short time. An investigation of the loose rings showed that they had loosened on their seats on the inner or base rings. Investigation then showed that a temperature rise of 70 to 80 deg. cent., combined with the high centrifugal stresses, would allow the rings to loosen very materially. It was then assumed that as the ring had heated up, bad contact had resulted between the inner and outer rings and this, in turn, had caused additional heating, so that the temperature rose rather suddenly after bad contact once formed. It developed later that this was probably not the true cause of the trouble, but at the time it was considered that the remedy for the trouble was in the use of rings which could be shrunk on with a greater tension.

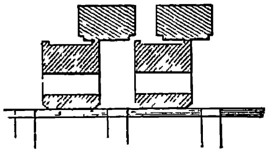


FIG. 10

It was then decided to try steel outer rings instead of bronze

on the end where the bronze rings had loosened. However, upon loading the machine, after applying the steel rings, a new difficulty was encountered. It was found that the loss was very greatly increased over that with the bronze rings. This loss was so excessive as to be prohibitive, as far as efficiency was concerned, and also the tests showed excessive heating of the rings and of the machine as a whole. Also, there were continual small sparks from the tips of the brushes, these sparks being from the iron itself, as indicated by their color and appearance. However, during the time these rings were operated there did not seem to be any undue wear of either the brushes or the rings, but obviously there was continued burning, as indicated by the sparks. With these steel rings it was found to be impossible to operate continuously at a current of 8000 amperes, due to the heating of the steel rings in particular and everything in general. At a load of 6000 amperes the loss was materially reduced and it was possible to operate continuously but with very high temperatures. The tests showed that, with the steel rings, at full rated current, the loss was approximately 200 kw. greater than with the bronze rings, or about 10 per cent of the output. With both ends equipped with steel rings, this would have been practically doubled.

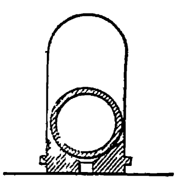


FIG. 11

While this was recognized as an entirely unsatisfactory operating condition, yet it allowed the machine to be run for a long enough period to determine a number of other defects which did not develop in the former test. One of these defects was an undue heating of the rotor pole face. This was obviously not due directly to bunching of the flux in the air gap on account of the open stator slots, for this heating did not appear when running with normal voltage without load. Further investigation showed that this was apparently due to some flux distorting effect of the stationary conductors in the stator slots, which carried about 4000 amperes each at rated load. On account of ample margin in the magnetizing coils the air gap was then materially increased, with some benefit. A further improvement resulted in the use of magnetic wedges, made of cast iron, in place of the non-magnetic wedges used before. These wedges are illustrated in Fig. 11. This produced a further beneficial effect, but there was still some extra heating in the pole face. Cylindrical grooves alternating $\frac{1}{2}$ in. and 1 in. deep

and about $\frac{1}{8}$ in. wide, with a $\frac{1}{4}$ in. web of steel between, were then turned in the pole face. The resultant pole face was therefore crudely laminated, as shown in Fig. 12. Also, on account of an apparent local heating of the metal bridge over the rotor slots, a narrow groove was cut in the closed bridge above each rotor slot, thus changing it to a partially open slot, as shown in the figure. This effectively eliminated the excess loss in the rotor pole face. This, however, led to another unexpected difficulty, which will be described later.

After this trouble was cured, the short circuit test was continued with a current of about 6000 amperes. After a considerable period of operation, a very serious difficulty in the operation of the machine began to show up, namely, trouble with lubrication. At first the lubrication was vaseline fed on to the rings by lubricating pads. This was apparently very effective for awhile, but eventually it was noted that slight sparking began, which, in some cases, would increase very rapidly and, in a comparatively short time, became so bad that the rings or brushes would become badly scored or blistered. Examination of the sparking brushes showed a coating of black "smudge" over the surface which seemed to have more or less insulating qualities. A series of tests then showed that whenever sparking began, the contact drop between a brush and the collector ring was fairly high and this drop increased as the sparking increased. For instance, it was found that on good, clean surfaces, the voltage drop between the brushes and the ring might be 0.3 to 0.5 volt. As each brush carried about 250 amperes at full load, this represented 75 to 125 watts per brush. When this contact resistance rose to about one volt, noticeable sparking would begin, the watts being, of course, proportionally higher, and when the contact drop became as high as two volts, representing about 500 watts per brush, very bad burning of the brushes and rings was liable to occur. A series of tests then showed that vaseline, or any other lubricating oil, would tend to form a coating over the brush contact and this coating would gradually burn, or be acted upon otherwise by the current, so that its resistance increased and the black smudge was formed which had more or less insulating qualities.

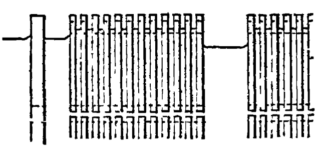


FIG. 12

A great number of tests were then carried out with various kinds of lubricants and it was found that anything of an oil or grease nature was troublesome sooner or later, as the smudge was formed on the brush contact. Then graphite, formed into cakes or brushes by means of high pessure, was tried on the rings and the results were very favorable compared with anything used before. In fact, the tests indicated that soft graphite blocks or brushes could furnish proper lubrication for the rings. The graphite is a conducting material, and a coating of it on the brush contact does not materially increase the resistance of the contact. This was supposed to have practically settled the question of lubrication and brush contact trouble, but experience later gave an entirely new turn to this matter.

While these tests were being carried on, a study of the ventilation of the machine was being made. The tests indicated that the end rings, that is, those next to the exciting coils, were considerably cooler than those near the center of the machine. However, as there were excessive losses and heating in the steel rings themselves, it was not possible to make any material improvement until the rings were changed.

The steel rings at one end of the rotor, and the bronze rings at the other end, were then removed and a second set of bronze rings was tried. These rings were specially treated in the manufacture so that the elastic limit was very high, and they were put on much tighter than in the former case. The load tests were then continued and the excess losses were again measured at various loads. It was found that the losses were very small compared with those of the steel rings, thus verifying the former results. The temperatures of the rings were much lower than with the steel, but it was found that the heating of the rings was unequal. It was finally determined that this unequal heating was due to the large external blowers which were driving the air over the rings in such a way as to heat those next to the center of the rotor to a much higher temperature than those at the outer ends. It was assumed at first that the air entering the axial holes through the core and blowing out between the rings as shown in Fig. 4, was more effective on the outer rings, and that this possibly caused the difference in temperatures. However, the radial holes at the outer ends were closed, and this made but little difference. The axial holes were then closed, and while the temperatures of the rings, as a whole, were increased, about the same difference as before was found between the end rings and the center ones.

It was then decided to remove the two large blowers to determine whether some other method of ventilation would be more effective. When this change was made the windage of the machine was greatly reduced and there was greater uniformity in the temperatures and the average temperature of the rings was only about 10 deg. higher than with the fans. Moreover, the windage loss was only about one-seventh as great as before, although the average temperature rise was not much higher, which indicated that the ventilation through the rotor holes was much more effective than that due to the blowers. In consequence, it was decided to increase the size of the axial holes through the rotor core from 2¾ in. to 3¾ in. diameter, and to "bell-mouth" them at their openings at the ends, in order to give a freer admission of air to the holes. When this was done it was found that the temperatures of the rings were lower than in any of the preceding tests, and moreover, they were fairly uniform. Also after the removal of the blowers, the objectionable noise, already referred to, was largely eliminated, so that it was not disagreeable to work around the machine. The graphite lubrication was continued with the bronze rings, on this test, and no difficulty was encountered, although the machine was operated for very considerable periods at approximately 8000 amperes.

On the basis of these tests, the machine was shipped to its destination and put in service. Then the real difficulties began—difficulties which were not encountered in the shop tests, principally because the conditions under which the machine operated in service were radically different from those at the shop, and also, because the shop test had not been continued long enough. This machine was operated in service, although not regularly, for a period of about two months, being shut down at times due to difficulties outside of the generating unit itself. However, this period of operation of the generator was suddenly ended by the stretching of one of the outer collector rings, which loosened it to such an extent that it ceased to rotate with the inner ring. This required the return of the rotor to the manufacturer.

This two months' operation gave data of great practical value, and in consequence, a number of minor difficulties were eliminated in the repaired rotor.

Upon the return of the rotor to the shop, an examination of the collector rings showed that the separate shrunk-on type of ring

was not practicable with any design of ring then at hand. Therefore, it was decided to make the collector rings in one solid piece with a very considerable wearing depth. This necessitated the removal of all the base rings and, in fact, it required a complete dismantling of the entire rotor winding. As the outer ring had loosened, there was a possibility of the base rings loosening in the same way, and therefore it was considered necessary to apply some scheme for preventing this loosening in case of sudden heating and expansion of any of the collector rings. It was then decided to apply some form of spring support underneath these rings, which could follow up any expansion in such a way as to keep the rings tight under any temperature conditions liable to be met with in practice. The spring support used consisted of a number of flat steel plates arranged around the rotor core, as indicated in Fig. 13. These plates were of such length and stiffness that a very high pressure was required to bend them down to conform with the rotor surface. These plates were arranged around the rotor core and drawn down with clamp rings until they fitted tightly against the mica. The collector ring was highly heated and slipped over the springs, the clamps being removed as the ring was slipped on. Tests were made to find at what temperature such a ring would loosen. While the best arrangement without springs would loosen at about 100 to 125 deg. cent., it was found that a ring supported, in the above manner, was still fairly tight at 180 deg. cent., which was far above any temperature which the machine would attain under any condition. It may be said here that, after several years' operation, this construction still appears to be first class, and no loosening of any sort has occurred.

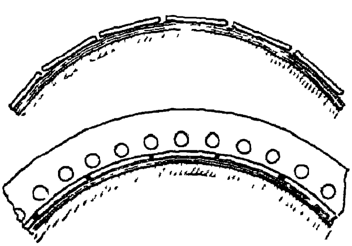


FIG. 13

In removing the winding from the rotor, it was discovered that the insulating tubes over the rotor conductors had traveled back and forth along the rods a certain amount. This travel, if continued for a long enough period, would apparently have injured the insulation, although no trouble had yet developed. Apparently, during heating and cooling, the expansion and contraction of the rods would carry the tubes with them lengthwise a very small amount. The tubes would then seat themselves in

the supporting rings or core and would not return to their original positions. It was found that in the slotted pole face already described, the webs or laminations of metal overhanging the rotor slots would hold the tube when the rod was traveling in one direction, but would sometimes allow the tube to move slightly when the rod traveled in the other direction, so that there was a sort of extremely slow ratchet action taking place. It was evidently necessary to have the tubes fit rather tightly in the retaining or supporting holes in the rings and the core, and to have the rods fit rather loosely in the tubes. Also, it appeared that shellac or other "gummy" material on the inner surface of the insulating tubes, was harmful, for wherever shellac was present the insulating tube always stuck to the rod and would tear at either side of such place. In consequence, the new set of tubes was made with a dry, hard finish on both the outside and the inside, and the inside surface was also paraf-

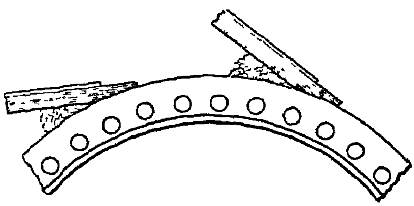


FIG. 14

fined. This, when carried out properly, served to remedy this trouble.

The reconstructed rotor, with the solid collector rings, was shipped to the customer and the service was continued. After operation for a considerable time, certain extremely serious difficulties appeared. One of these was brush trouble, and another was undue wear of the rings.

The brush trouble was a most discouraging one. The machine was located in an engine room adjacent to a rock-crushing building. Fine dust was always floating around the machine and, this dust continuously passing through the machine tended to form a deposit immediately behind the brushes as shown in Fig. 14. This dust packed in rather solidly behind the brush, due to the high speed of the rings, and eventually it tended to lift the brushes away from the rings. It also showed a tendency to get under the brush contact, with consequent increased resistance of contact. Frequent removal and cleaning of the brushes was

impracticable, as they were not sufficiently accessible to do this readily. This rock dust, packed behind the brushes, also had a scouring or grinding action on the rings themselves. Accompanying this was an undue rate of wear of the rings. This, however, was not entirely mechanical wear, as it appeared also to be dependent upon the current carried and was, to some extent, due to a burning action under the brush which tended to eat away the surface of the rings. However, while the undue wear was not altogether due to dust back of the brushes, yet this accumulation of dust appeared to have a very harmful action on the machine. Various methods were considered for overcoming this collection of dust, one of which consisted of enclosed air inlets to the machine, fitted with screens for sifting out the dust. This lessened the trouble to some extent, but it was evident that it would not cure it entirely, as the entire machine was so located that dust could come in around the brush holders without going through the ventilating channels.

The method finally adopted for overcoming the difficulty of accumulation of dirt was rather startling. It was casually suggested that the copper leaf brushes be turned around so that *the rings would run against the brushes*, so that the dirt or dust over the rings would be " skimmed off " by the forward edge of the brushes. This obviously would prevent the collection of dirt, but the question of running thin leaf copper brushes on a collector ring operated at a speed of about 220 feet per second (or 13,200 feet per minute) looked like an absurdity to any one with experience in electrical machinery, so that we all hesitated at first to consider the possibility of it. However, as something had to be done, the writer suggested to the engineer in charge, that he change the brushes on one of the rings so that they would be inclined against the direction of rotation. This gave no trouble and the other brushes were then changed to the same direction and the operation ever since has been carried on with this arrangement. To the writer this has always seemed an almost unbelievable condition of operation, but as there has not been a single case of trouble from this arrangement during several years of operation, one is forced to believe that it is all right. This change entirely overcame the trouble from accumulation of dirt. However, it did not entirely cure the burning of the brushes and rings above described, but rendered the matter of lubrication somewhat easier than at first.

As to the other serious trouble, it was mentioned that there

was a burning action under the brushes which tended to " eat " or " wear " away the surface of the rings. This also tended to burn away the brush surfaces, the amount of burning in either case depending, to a considerable extent, upon the direction of the current. At one side of the machine the brushes would wear more rapidly, while at the other side the rings would wear faster. The polarity of the current was influential in this action. Particles of the metal appeared to travel in the direction of the current; that is, where the current was from the ring to the brushes, the ring would wear more rapidly, while the brush would show but little wear, while at the other end of the machine, the opposite effect would be found. However, the particles of metal taken from the ring did not deposit, or " build up," on the brushes.

During all this operation, graphite had been used for lubrication. In the earlier stages, powdered graphite compressed into blocks, had been used. Later it was found that very soft graphite brushes in insulated holders would give ample lubrication for the rings. However, even with this lubrication and the removal of the dirt trouble, there was still an appreciable burning of the brushes and rings as indicated by the more rapid wear of the rings at one end of the rotor, and of the brushes at the other end. Extended tests showed that this burning was a function of the contact drop between the brushes and the rings. Neither the rings nor the brushes would burn appreciably if the contact drop between the brushes and the ring could be kept very low. When this drop became relatively high (about one volt), the rings or brushes would show an undue rate of wear. It was found also that, after a considerable period of operation, it was very difficult to obtain a low brush contact drop, as the brush wearing surface became coated with a sort of " smudge," which seemed to have resisting qualities. An analysis of this coating showed a very considerable amount of zinc in it, and it was determined that the zinc in the collector rings was burning out and forming an insulating coating on the brush contacts. The remedy for this condition was the application of some cleaning agent which would chemically act on the smudge and dissolve it or destroy its insulating qualities. The right material for this purpose was found to be a weak solution of muriatic acid—about 4 per cent in water. When this was applied to the rings by means of a " wiper," at intervals, the brush contact drop could be reduced to a very low figure— frequently to 0.1 or 0.2 of a volt,

and the rings would take on a very bright polish. Also, while this low contact drop was maintained it was found that the rings showed an almost inappreciable rate of wear. However, one set of rings continued to wear somewhat faster than the other. This difficulty of unequal wear of the two sets of rings was overcome by arranging a switch so that the polarity of the two ends of the machine could be changed occasionally.

The temperature of the machine was reduced by the above treatment of the rings. Obviously, part of the heat was due to the loss at the brush contacts, which, of course, was reduced directly as the contact drop was reduced.

The machine was now running quite decently with compara tively heavy loads, from 7000 to 10,000 amperes, and the only trouble was in several minor difficulties which were then taken up, one at a time, in order to ascertain a suitable remedy. These difficulties, however, were not interfering with the regular operation of the machine.

One of the difficulties which finally developed was due to stray magnetic fluxes through the bearings. These fluxes, passing out through the shaft to the shell of the bearing, constituted, in themselves, the elements of a small unipolar machine, of which the bearing metal served as collecting brushes. The e.m.f. generated in the shaft was a maximum across the two ends of the bearing. Consequently the current collected from the shaft by the bearing metal should have been greatest near the ends of the bearing, and least at the center. This was the case as indicated by the appearance of the bearing itself, which showed evidence of pitting near the ends but none at the center.

To remedy this trouble, a small demagnetizing coil was placed outside the stator frame, at each end of the rotor, between the rotor core and the bearings. These coils were excited by direct current which was adjusted in value until practically zero e.m.f. was indicated on the shaft at the two ends of each bearing. This indicated that the unipolar action was practically eliminated. This arrangement has been in use ever since it was installed, and no more trouble of any sort has been encountered from local currents in the bearings or elsewhere.

Some of the brushes did not show as good wearing qualities as desired and various experiments were made with different combinations of materials and various thicknesses and arrangement of the brush laminæ. Brass leaf brushes were tried; also, mixtures of copper, brass, aluminum and various other leaf metals

in combination. None of these showed any better than the thin copper leaf brush. The tests finally showed that such a brush, very soft and flexible, with a suitable spring tension, would give very satisfactory results. Also instead, of two brushes side by side, a single brush, covering the full width of a ring, was found to be more satisfactory. Some tests were also made with carbon brushes, consisting of a combination of carbon or graphite combined with some metal, such as copper, in a finely divided state. These brushes were claimed to have a very high carrying capacity and also to have a certain amount of self-lubrication. A set of these brushes was tried on one of the rings, but lasted only for a very short time. The apparent wear was rapid, but it is not known whether this was due to the very high speed of the collector rings, or rapid burning away of the brush or the inability of this type of brush to quickly follow any inequalities of the collector rings. This test was abandoned in a comparatively short time.

After getting rid of the old troubles, a new and unexpected one had to appear. For some unknown reason, the insulating tubes on the rotor conductors began to break down; also grounds occurred between the collector rings and the core.

On account of the delay required in making any changes in the rings or rotor winding, the customer arranged with the manufacturer to have a new rotor built as a reserve, as it was obvious that sooner or later there would have to be considerable reconstruction of the insulation on the first rotor due to unexplained short circuits and grounds. A new rotor was at once constructed, embodying all the good features of the first rotor, with some supposedly minor improvements. The old rotor was then removed for investigation and repairs. The cause of the breakdowns of the insulation on the tubes was then discovered. The air entering through the axial rotor holes and passing out through the radial holes between the rings, carried fine particles of cement or crushed stone dust and this had "sand-blasted" the under side of the tubes. When the rotor had been operated during the preliminary two months' period, previously described, before the replacement of the rings, no evidence of this sand-blasting had been visible. Investigation showed that the insulating tubes in the former winding had been made with a fullerboard base, which is rather soft and fibrous in its construction. The tubes on the second winding had been made with "fish" paper instead of fullerboard, in order to give a hard finish on the

inside and outside. It was due to this hard material that the troubles from sand blasting occurred. However, fish paper tubes were superior to the fullerboard in strength and other qualities, and as they were inferior only, in this one characteristic, they were used again in rewinding the rotor, but whereever the tubes were exposed in passing from one ring to the next, they were taped over with several layers of soft tape whch was also sewed. This gave a soft finish which would resist sandblasting, and no trouble from this source has occurred for several years.

From the breakdowns to ground, it was evident that an entire replacement of the rings was necessary in order to repair the mica bush or sleeve lying beneath the rings. This required the removal of the entire rotor winding and rings. It was found that cement dust coming up through the radial holes had sifted in through various crevices or openings around the holes and that, finally, conducting surfaces and paths were formed which allowed the current to leak to ground sufficient to eventually burn the insulation. Therefore, when replacing the mica sleeve over the rotor, extra care was taken to fit insulating bushings at the top of the radial holes in such a way as to seal or close all joints, thus allowing no leakage paths between collector rings and the body of the core. This is shown in Fig. 15. No further trouble has occurred at this point.

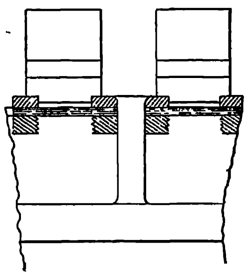


FIG. 15

In removing the collector rings for these repairs, it was found that the flat spring supports shown in Fig. 13 had been entirely effective and there was no evidence whatever of any disturbance of the rings on the core, and there was no injury to the mica, such as would be shown by any slight movement. The rings were also very tight so that it took a very considerable temperature to loosen them sufficiently for removal.

In view of the delay and expense of repairing one of these rotors when the collector rings had to be removed, with the possibility of damaging the insulating tubes over the conductors, and the insulating bush over the core, it was then decided that a movable wearing ring was practically necessary in order to make this machine a permanent success. Therefore, the problem of a separate outside wearing ring, as originally con-

templated, was again taken up. The difficulty, already described, of the zinc burning from the rings and forming a coating on the brushes, indicated that some other material, without such a large percentage of zinc, should give better results. The difficulty was to obtain such a material, with suitable characteristics otherwise. All data at hand showed that rings, with desirable characteristics electrically, did not have the proper elastic limits, or proper expansion properties when heated. In other words, when such rings were shrunk on the base or supporting ring they would stretch to such an extent, when cooled, that they would become loose again with very moderate increase in temperature. The solution of this problem of a separate ring construction was found in the use of some spring arrangement underneath the outer ring which would still keep it tight on the inner ring even when hot. The spring arrangement

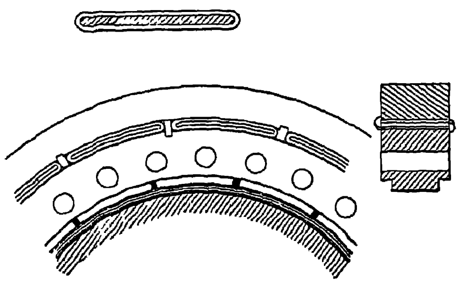


FIG. 16

used under the inner rings, as shown in Fig. 13 was then applied with certain modifications. In order to get good contact between the inner and outer rings for carrying the current, each of these steel springs or plates was covered by a thin sheet of copper as shown in Fig. 16. While each copper sheet was of comparatively small section, the large number of springs used gave sufficient total copper to carry the current from the outer to the inner or base ring without any danger of current passing through the spring plates themselves. This arrangement was used in reconstructing this rotor and has proven entirely successful.

In order to determine the effects of various materials without zinc, or with but a small quantity of it, a number of rings were fitted up on a test rig and were operated for long periods with currents, up to 12,000 amperes in some cases. In these tests,

four different kinds of material were used, all of them representing different mixtures of copper with a small percentage of other materials but with little zinc in any of them. It was feared that copper brushes on the copper rings would not work satisfactorily, but while there was apparently some difference between the action of the different rings, it was found that copper brushes running on copper were, in general, satisfactory. The brushes were in-clined against the rings, as in the actual machine, during this series of tests.

These tests were carried through with various numbers of brushes, etc. It was found that the number of brushes could be reduced to about one-third the full number, and still collect the total rated current, but that any great reduction from the full number of brushes made the operation of the rings and brushes more sensitive, and more attention was required to keep them in perfect condition. It was also found that any hardness or undue "springiness" in the brushes, or brush material, would tend to give increased wear. Brushes of very thin leaf copper, eventually gave best results. It was also shown by these tests that if a very good polish could be maintained on the rings, the rate of wear from day to day was practically unmeasurable on account of its smallness.

As a result of these ring tests, the rotor undergoing repair was equipped with outside copper wearing rings, spring supported. The material in the rings was about 92 per cent pure copper, 2 per cent zinc and 6 per cent tin.

The rotor was then installed in service and has been operating steadily for several years, with entire success. The other rotor, which had been operating while this rotor was being repaired, was then thoroughly examined after removal, to determine any possible defects. It was noted that the insulating tubes over the rotor conductors were badly cracked or buckled in a number of places. Upon removal of the rods or conductors it was found that the insulating tubes were stuck so tightly to the copper rods that they would be torn in pieces in trying to remove them. As it had been intended that these tubes should move freely on the rods or conductors, as previously described, it was evident that there was something radically wrong. The true cause of the trouble was then discovered. In first fitting this set of tubes over the rods, they had been too tight, and, in order to make them fit easily, the men who assembled the machine had reamed them on the inside to enlarge

them, and, in doing so, had cut away the inner hard sheet of fish paper which had formed the lining, thus exposing a shellaced surface. As soon as heated, this shellac stuck the tube to the rod so that there could be no possible movement between the two. In consequence, when the rods expanded or contracted, the tubes moved backward and forward in the supporting holes, and wherever they stuck fast in the outer holes, something had to give, so that eventually the tubes buckled or cracked or pulled open. This was readily remedied by putting on new tubes properly constructed. As the rings on this rotor were in very good condition with but little worn away, the removable type of ring was not added, as this would require turning off a large amount of effective material on the existing rings and replacing it with new outer rings. It was decided that as there was several years' wear in the old rings, it would be of no material advantage to throw this away when it could be worn away in service, just as well as it could be turned off in a lathe. After the rings in this machine are worn down the permissible depth, they will be refilled by the addition of the removable type.

This unipolar generator has now been in service for quite a long period, with no difficulty whatever, and with an average ring wear of less than 0.001 in. per day, or less than $\frac{3}{8}$ in. per year. This may seem like an undue rate of wear; but in reality it is an extremely low rate, if the high peripheral speed, and the number of brushes, are considered. This machine operates day and night, seven days in the week, and practically continuously during the entire year. Taking the peripheral speed into account, the above rate of wear represents a total travel of each ring of about 3.6 million miles for each inch depth of wear, or about 150 times around the earth along a great circle. Considering that there are brushes bearing on each ring at intervals of about eight in., a wear of one in., for every 3.6 million miles traveled, does not seem unduly large. If, at the same time, it is considered that the brushes are collecting from 7500 to 10,000 amperes from each ring on a total ring surface of about $3\frac{1}{2}$ in. wide by 42 in. diameter, it is not surprising that there should be more or less " wear " due to the collection of this current. In fact, the current collected averages from 16 to 20 amperes per square inch of the total ring wearing surface. This may be compared with standard practice with large d-c. commutators, in which $1\frac{1}{2}$ to 2 amperes per square inch of commutator face is usual and 3 amperes is extreme.

On account of the final success of this machine, the story of its development is a more pleasant one to tell than is the case in some instances where entirely new types of apparatus are undertaken. It might be said, after reviewing the foregoing description, that many of the troubles encountered with this machine could have been foreseen; but such a statement would be open to question, for the engineers of the manufacturing company were in frequent session on all the various phases and difficulties which developed. The writer knows that in many cases, after any individual trouble was known, suggestion for remedies were not readily forthcoming. The writer does not know of any individual machine where more engineering and manufacturing skill was expended in endeavoring to bring about success, than was the case with this machine. As an example of engineering pertinacity, this machine is possibly without a rival. A mere telling of the story cannot give more than a slight idea of the actual fight to overcome the various difficulties encountered in the development of this machine.

The results obtained were valuable in many ways. Many data were obtained which have since been of great use, both from a theoretical as well as a practical standpoint, in other classes of apparatus. Certain fundamental conditions encountered in this machine have led to the study of other allied principles which point toward possibilities in other lines of endeavor. Therefore this machine, which was very costly in its development, may eventually pay for itself through improvements and developments in other lines of design.

The writer wishes to say a good word for the purchaser of this new apparatus. He was long-suffering, and was undoubtedly put to more or less trouble and inconvenience, but nevertheless he gave opportunity to correct difficulties. He recognized that the engineers were confronted with a new problem in this machine and he gave them an opportunity to carry it through to success. Apparatus of this type could only be developed to full success in commerical operation, as all the difficulties encountered would never have been found on shop test. Therefore, the attitude of the customer was of prime importance in the development of such a machine.

COMMUTATING POLES IN SYNCHRONOUS CONVERTERS

FOREWORD—About 1909, the use of commutating poles in synchronous converters was being studied. Suggestions were made from time to time that our usual slow speed rotary converters should have interpoles. The author, therefore, prepared a short article, explaining wherein commutating poles would be of less value to rotary converters, of the then usual speeds and constructions, than they would be on direct-current generators.

"Late in September, 1910, the Chairman of the Papers Committee of the American Institute of Electrical Engineers asked the author whether he had any material which could be prepared for the Institute on very short notice. A rough draft of this article was submitted and was at once accepted, with instructions to complete it for the following November meeting. The author called to his aid, Mr. F. D. Newbury, who added about one-half more, covering principally material on existing types of rotaries. Most of this latter part has been omitted from this reprint, but the author's discussion at the Institute meeting has been incorporated as it forms a technical continuation of the first part of the paper and brings out that the real need for commutating poles in rotary converters would come with higher speeds."

This paper states that the short-circuiting effect of the dampers surrounding the commutating poles is considered harmful. However later experience has shown that the increased damping effect of this arrangement more than compensates for the harmful effects.

As this paper was written before the term "commutating pole" was adopted as standard, the term "interpole" has been used throughout.—(ED.)

SYNCHRONOUS converters with interpoles have been used but little in this country up to the present time (1910). Considering that interpole generators and motors have come into extensive use in this country, the question will naturally be raised why interpole converters have not come into similarly extensive use. The reply might be that the introduction of any new type of apparatus is a relatively slow process; but, on the other hand, interpoles on direct current generators and motors came into general use in a relatively short time, especially so in railway motors. This indicates that there has been a more or less pressing need for interpoles in certain classes of apparatus and the greater the need for the change the quicker was the change made.

Any important change in design or type must be justified

by engineering and commercial reasons, such as improved performance greater economy, or lower cost. In the railway motor, placed under the car, and more or less inaccessible, improved operation at the brushes and commutator, when equipped with interpoles, represented a pressing reason for the change in type, although the cost and efficiency were not appreciably changed. In the direct-current generator with the modern tendency toward higher speeds with lower cost, the interpoles represented a practical necessity. This has been recognized for several years and the change to the interpole type has been made as rapidly as circumstances will permit. Also, in variable-speed direct-current motors interpoles have been in general use for a number of years, simply because the interpoles represent a very definite improvement in a number of ways.

New types of apparatus should only be introduced where they represent some distinct improvement or advance over existing types. Where a new type does not represent such improvement and is simply introduced to gratify a personal whim of the purchaser, or desire on the part of a manufacturing company to produce something different from other companies, the new apparatus, as a rule, will not advance quickly into public favor since there is no real necessity for it.

It is therefore a question whether the slowness in the introduction of interpoles in synchronous converters is due to lack of sufficient advantages, or American engineers do not sufficiently appreciate their advantages. There appears to be room for wide differences in opinion on this subject. The synchronous converter and the direct-current generator are two quite different machines, in their characteristics, and no one can say off hand, that interpoles will give the same results in both. In the following is given a partial analysis of the conditions occurring in the two classes of machines, which will indicate wherein interpoles are of greater advantage on direct-current generators than on converters.

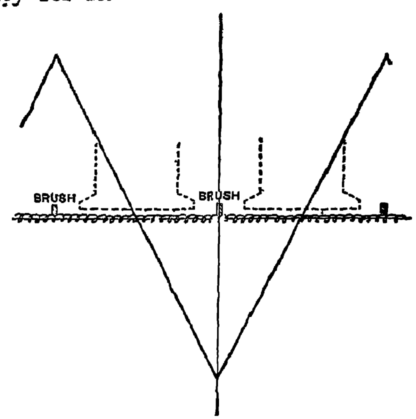


Fig. 1

Taking up first, the direct current generator, it may be considered as containing two sets of magnetizing coils, namely, the armature and the field windings. Considering the armature winding alone, the magnetomotive force of the armature winding has zero values at points midway between two adjacent brush arms or points of collection of current and rises at a uniform rate to the point of the winding which is in contact with the brushes. This is illustrated in Fig. 1. Therefore the armature winding has its maximum magnetizing effect or magnetomotive force at that part of the core surface where the winding is directly in contact with the brushes. However, the magnetic flux set up by the armature winding will not necessarily be a maximum at this point, as this depends upon the arrangement of the magnetic or other material surrounding the armature. If this point occurs midway between two field poles, then, while the magnetizing effect is greatest at this point, the presence of a large air-gap at this same point may mean a relatively small magnetic flux, while a much higher flux may be set up by the armature winding at the edges of the adjacent field poles. In the usual direct-current generator construction without interpoles, the position of commutation is almost midway between two adjacent poles and therefore the point of maximum magnetomotive force of the armature is also practically midway between poles. The absence of good magnetic material over the armature at this point serves to lessen the magnetic flux due to the armature magnetizing effect, but even with the best possible proportions there will necessarily be a slight magnetic flux set up at this point. While this field is usually of small value, yet unfortunately it is of such a polarity as to have a harmful effect on the commutation of the machine. During the operation of commutation, the coil which is being commutated has its two terminals short-circuited by the brushes. If this short circuited coil at this moment is moving across a magnetic flux or field, it will have an e.m.f. set up in it which will tend to cause a local or short circuit current to flow. Such a current is set up by the flux due to the armature magnetomotive force described above and unfortunately this current flows in such a way as to give the same effect as an increased external or working current to be reversed as the coil passes from under the brush. In other words, the e.m.f. set up in the short circuited coil by the above field adds to the e.m.f. of self induction in the coil due to the reversal of the working current.

Another cause of difficulty in the commutation of a direct current machine is the self induction of the armature coils as they individually have the current reversed in them in passing from one side of the brush to the other. Each coil has a local magnetic field around itself, set up by current in itself and its neighboring coils. The value of this local magnetic field depends upon the arrangement of the winding, the disposition of the magnetic structure around the coil, the ampere turns, etc. During the act of commutation, that part of the local field due to the coil which is being commutated must be reversed in direction. It is therefore desirable to make the local field due to any individual coil as small as possible. This means that the number of turns per coil should be as low as possible, the amperes per coil also should be as small as possible, while the magnetic conditions surrounding the coil should be such as to give the highest reluctance. By the proper arrangement of the various parts, it is usually found that the e.m.f. of self induction, due to the reversal of the coil passing under the brush, can be made of comparatively small value so that, if no other conditions interfere, good commutation could be obtained under practically all commercial operating conditions. However, the magnetic field between the poles set up by the armature magnetomotive force as a whole, as described above, adds very greatly to the difficulties of commutation. If the armature magnetomotive force, or the field due to it, could be suppressed, then one of the principal limitations in the design and operation of direct-current generators would be removed, and the commutation limits would be greatly extended. Or, better still, if a magnetic flux in the reverse direction were established at the point of commutation, then the e.m.f. set up by this would be in opposition to the e.m.f. of self induction of the commutated coil and would actually assist in the commutation.

This latter is what is accomplished by interpoles. When these are used the brushes on the commutator are so placed that the short circuited or commutated coils are directly under the interpole. Consequently, the maximum magnetomotive force of the armature is in exact opposition to that of the interpoles. Therefore, the total ampere turns on the interpoles should be equal to the total ampere turns on the armature in order to produce zero magnetic flux under the interpole or at the point of commutation But, for best conditions there should not be zero field, but a slight field in the opposite direction from that which the armature winding alone would produce. Therefore, the magneto-

motive force of the interpole must be greater than that of the armature by an amount sufficient to set up a local field under the interpole which will establish an e.m.f. in the short circuited coils opposite to that set up by the commutated coils themselves and practically equal to it. The excess ampere turns required on the commutated poles is therefore for magnetizing purposes only and the amount of extra ampere turns will depend upon the value of the commutating field required, depth of air-gap under the commutating pole, etc. The commutating field required is obviously a function of the self induction of the commutated coil and evidently the lower the self induction the less commutating field will be required. It is evident therefore that the commutating field under the commutating pole bears no fixed relation to the armature ampere turns or to the main field ampere turns, but is, to a certain extent, dependent upon the proportions of each individual machine.

It is evident that the magnetomotive force of a given armature varies directly with the current delivered, regardless of the voltage. Therefore, that part of the interpole magnetomotive force which neutralizes that of the armature should also vary directly in proportion to the armature current. Also, the self induction of the commutated coils will vary in proportion to the armature current carried, and therefore the magnetic field under the interpole for neutralizing this self induction should also vary in proportion to the armature current. It is therefore obvious that if the main armature current be put through the interpole winding, the magnetomotive force of this winding will vary in the proper proportion to give correct commutating conditions as the armature current varies, regardless of the voltage of the machine. This is on the assumption that the entire magnetomotive force of the interpole winding is effective at the air gap and armature, which implies an absence of saturation in the interpole magnetic circuit. In the usual construction, the interpole winding always carries the main armature current as indicated above.

One consequence of the use of the interpole is that somewhat less regard need be paid to keeping the self induction of the commutating coil at its lowest value. In consequence, there is somewhat more freedom in proportioning the armature winding, slots, etc., than in a non-interpole machine, and advantage can be taken of this in bettering the proportions for other characteristics.

The conditions of design are therefore not as rigid in the interpole as in the non-interpole type.

The above description of the interpole generator has been gone into rather fully, as many of the points mentioned will be referred to again in connection with interpoles on synchronous converters.

The synchronous converter differs from the direct current generator in one very important particular, namely, it may be considered as motor and generator combined. It receives current from a supply system the same as a motor and it delivers current to another system like a direct-current generator. The magnetomotive force of the armature winding as a motor acts in one direction, while the magnetomotive force of the armature winding as a generator acts in the opposite direction. As the input is practically equal to the output, it is evident that these two armature magnetomotive forces should practically neutralize each other, on the assumption that the armature magnetomotive force, due to the polyphase current supplied has practically the same distribution as that of the corresponding direct-current winding. Assuming that the two practically balance each other, then it is evident that one of the principal sources of commutation difficulty in direct current generators

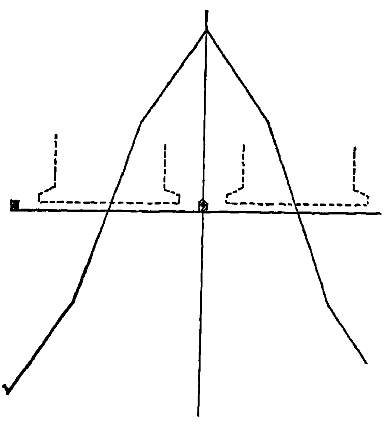


FIG. 2

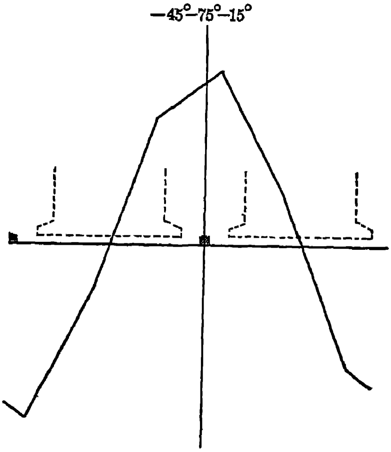


FIG. 3

is absent in the converter and therefore the limits in commutation should be much higher than those of direct-current machines.

The following diagrams show the distribution of the alternating-current and direct-current magnetomotive forces on a six-phase rotary converter. The magnetomotive force distribution for the alternating-current input is plotted for several different positions of the armature. Three different positions are shown with the armatures displaced successively 15 electrical degrees. The general forms of these distributions repeat themselves for further similar displacements.

These distributions are illustrated in Figs. 2, 3 and 4. It is evident from these three figures that the peak value of the magnetomotive force the armature varies as the armature is rotated, as indicated by the heights of the center line in the three figures.

In Fig. 5, the magnetomotive force distribution of Fig. 2 and the corresponding direct-current distribution of Fig. 1 are both shown, but in opposition to each other. In this figure both are shown in proper proportion to each other, taking into account the alternating current amperes and the direct-current amperes output. The resultant of these two distributions is also indicated in these figures.

In Fig. 6 the distributions correspond to Figs. 3 and 1 combined and the resultant is also shown.

Fig. 7 combines Figs. 4 and 1.

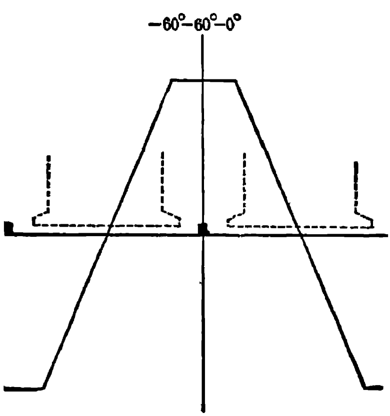


FIG. 4

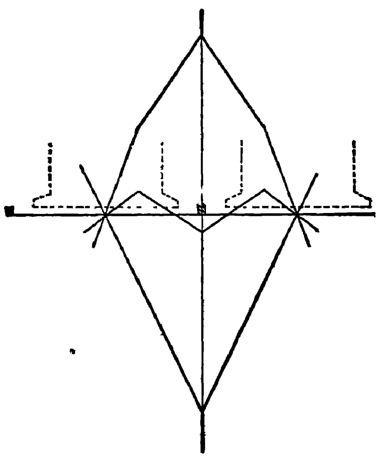


FIG. 5

It is the resultant magnetomotive force in these three figures which is important, as this is the effective magnetomotive force which tends to produce a flux or field over the commutated

coil. It is evident from these figures, which are drawn to scale, that this resultant varies in height as the armature is rotated, but the maximum is only a relatively small per cent of the direct-current magnetomotive force. Therefore, it is obvious that one of the principal sources of difficulty in the commutation of the direct-current generator is practically absent in the converter, and it is also evident from this that the commutating conditions in the latter should be materially easier than in the former. This has proved to be true by wide experience in the construction and operation of converters.

In the above figures the magnetomotive forces have been plotted to scale on the following basis:

The six-phase converter winding is connected to three transformers with the so-called diametral arrangement; each of the three secondaries is connected across the diameter, or across 180 deg. points on the winding, the three diameters being displaced 60 deg. with respect to each other. Assuming the direct current in the winding as A, then the maximum value of the alternating current in any one phase of the alternating-current end will be equal to $\frac{2}{3}$ A, or 0.667 A, assuming 100 per cent efficiency. However, as the alternating-current input must be somewhat greater than the direct-current output, due to certain

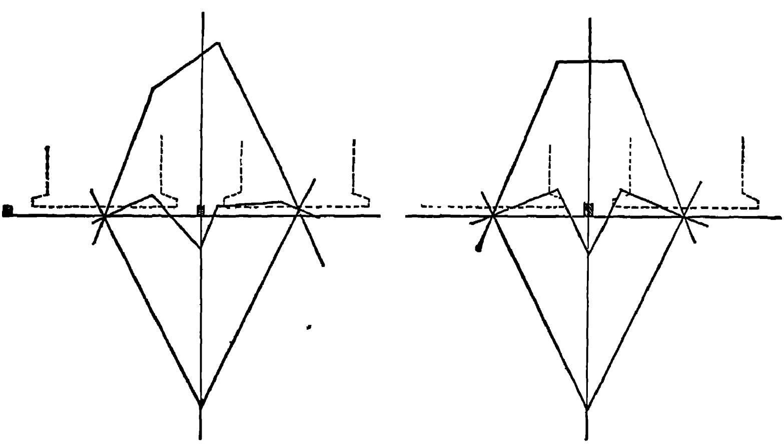


FIG. 6 FIG. 7

losses in the machine, it is evident that the maximum alternating current in any one phase must be somewhat greater than 0.667 A. The field copper losses may be considered as part of

the output of the rotary. The armature copper losess may be considered as due to an ohmic drop between the counter e.m.f. of the armature and the transformer e.m.f., and simply a higher transformer e.m.f. must be supplied to overcome this drop and therefore it does not effect the true current input of the rotary. However, the losses due to rotation, such as iron loss and the friction and windage are excess losses which represent extra current which must be supplied to the alternating-current end of the rotary. These rotational losses will usually be relatively small in a 25-cycle converter, being possibly 4 per cent or 5 per cent in a small machine and $1\frac{1}{2}$ per cent to 3 per cent in a large machine. In the 60-cycle converters, where the iron losses are relatively higher and the speeds are somewhat higher, giving greater friction and windage, the rotation losses may be considerably greater than on 25-cycle machines. Assuming these rotation losses will be 3 per cent, then the maximum alternating current per phase $= \frac{0.667\,A}{0.97} = 0.687\,A$. The foregoing Figs. 5, 6 and 7 are worked out on this assumption of 97 per cent rotational efficiency and on this basis of minimum value of the resultant magnetomotive force of the armature at the direct-current brush is about 7 per cent of the direct-current magnetomotive force of the same wording, while the maximum value is about 20 per cent. The lower the rotational efficiency the smaller would be these values, and with a rotational efficiency of about 89 per cent, the minimum resultant would fall to zero, while the maximum value would be about 13 per cent.

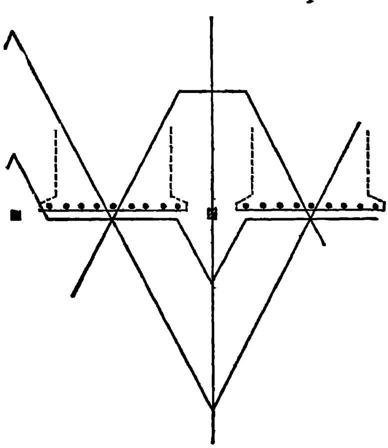


Fig. 8

The resultant magnetomotive force of a synchronous converter might be compared with that of a direct-current generator with compensating windings in the pole faces. It is generally known that such direct-current generators have much better commutating conditions than ordinary uncompensated machines. If such compensating winding on the field of a direct-current machine covered symmetrically the whole armature surface,

then the armature reaction could be completely annulled, which is not the case in the converter. But with compensating windings located only in the pole faces, then the armature magnetomotive force midway between the poles could not be completely annulled, unless over-compensation is used, and the resultant would be as shown in Fig. 8, which is not quite as good as the average resultant in the converter. The commutating conditions in the converter can therefore be considered as at least

In the application of interpoles to the synchronous converter the same principles should hold as in a direct-current generator, namely. the interpole magnetomotive force should be sufficient to neutralize that of the armature winding and, in addition, should set up a small magnetic flux sufficient to overcome the self induction of the commutated coil. As the magnetomotive force the armature varies between 7 per cent and 20 per cent shown in the above figures, it is evident that perfect compensation of this cannot be obtained and that therefore only some average value can be applied. Assuming that 15 per cent will be required on the average to compensate for this, then in addition the interpole winding must carry ampere turns sufficient to set up the small magnetic field for commutation. Thus the total ampere turns on the interpole will be equal to 15 per cent of the armature direct-current ampere turns plus a small addition for setting up the useful or commutating field. In the direct-current generator, the ampere turns on the interpoles must equal the total armature ampere turns plus a corresponding addition for the commutating field. It is therefore evident that an interpole winding on a converter will naturally be very much smaller than on a direct-current generator, and in general it is between 25 per cent and 40 per cent of the direct-current.

In the pulsating resultant magnetomotive force in the converter there lies one possible source of trouble with interpoles Assume, for example, the total ampere turns on the interpoles are equal to 30 per cent of the direct-current ampere turns on the rotary and that 15 per cent of this is for overcoming the average value of the resultant magnetomotive force, then an average of 15 per cent will be available for setting up a commutating field; but, according to the above diagrams, the resultant magnetomotive force of the armature varies from 7 per cent to 20 per cent. With a total interpole winding representing 30 per cent,

then the effective or magnetizing part will vary from 30–7 to 30–20; that is, from 23 per cent to 10 per cent. The effective magnetomotive force therefore tends to vary over quite a wide range so that the commutating field would also tend to vary up or down over a very considerable range, which is an undesirable thing for commutation. However, as this pulsation is at a fairly high frequency it tends to damp itself out by setting up eddy currents in the structure of the magnetic circuit. If a good conducting damper or closed circuit were placed around the interpole, it is probable that this pulsation would be almost completely eliminated, but such a damper possesses certain disadvantages, as will be shown later.

In practice this pulsation of the armature reaction under the interpoles is apparently not noticeably harmful in most cases, as evidenced by the fact that well-proportioned interpole converters in commercial service show no undue trouble at the commutator or brushes.

Due to the relatively small number of ampere turns required on the interpole of a converter compared with those required on a direct-current generator, the design of the interpoles in the two cases presents quite different problems. In the direct-current generator the interpoles carry ampere turns, which in all cases are greater than the armature ampere turns, as explained before. As the field ampere turns on the main poles are, not infrequently, but little greater than the armature ampere turns, it is evident that the interpole winding may, in some cases, carry as many ampere turns as the main field windings. While but a small per cent of these interpole windings is effective in producing flux under the pole tip, yet they are all effective in producing leakage from the sides of the poles. As the interpoles are generally small in section compared with the main poles, and as they may carry ampere turns equal to the main poles, it is evident that the effect of leakage may be relatively great on the interpole.

For instance, if the leakage on the main poles is 15 per cent of the useful flux, then, with the same total leakage on the interpoles, this may represent a very high value compared with the useful flux, due to the small section of the interpole and the relatively low useful interpole flux. In consequence, it is considerable of a problem to proportion the interpoles of a direct current generator so that the leakage flux will not saturate the interpoles at some part of the circuit. If they saturate, then

part of the ampere turns on the interpole are expended in such saturation and the part thus expended must be counted off from the extra or excess interpole ampere turns. If, for example, the interpole winding requires 100 per cent for overcoming the armature and there is 20 per cent extra ampere turns for setting up a useful flux, then any saturation in the interpole circuit must represent additional ampere turns on the field, as the above 120 per cent is necessary for useful flux and for neutralizing the armature. With reduced current, and consequent lower saturation, these additional interpole turns become effective in magnetizing the gap and thus the commutating flux is too strong. At greatly increased load, more ampere turns are required for saturation, and the commutating flux is altogether too weak. It is thus evident that a machine with highly saturated interpoles will not commutate equally well for all loads. Herein lies a problem in the design of interpole generators, as it is difficult to maintain a relatively low saturation in the interpoles due to their small section and high ampere turns which cause leakage. It is well known that in the main poles of the generator, a leakage flux which is higher than the useful flux is objectionable, from the designer's standpoint; and yet in the use of interpoles this is a normal condition rather than an exception.

In the synchronous converter the conditions are somewhat different due to the fact that the interpole ampere turns are usually only 25 per cent to 40 per cent as great as on a corresponding direct-current generator. The leakage at the sides of the poles becomes relatively much less, while the useful induction remains about the same as on the direct-current generator. In consequence, saturation of the poles is not so difficult to avoid. In some cases, due to the smaller ampere turns on the interpole winding, the interpole coils can be located nearer the pole tip and thus the leakage can be further reduced. However, the placing of the interpole coil over the whole length of the pole is not as objectionable in the converter interpole as it is on the direct-current generator as the ampere turns are less. It is those ampere turns which are located close to the yoke, or furthest away from the pole tip, which produce the highest leakage, while those close to the pole tip usually produce much less leakage, but in interpole generators with their high number of ampere turns on the interpoles it is often difficult to find space for the interpole winding, even if distributed over the whole pole length. In some cases, a direct-current machine may be larger than

would otherwise be required, simply to obtain space for the interpole winding. This is not true to the same extent in the application of interpoles to converters.

In the above the leakage is referred to as a function of the interpole winding as if the main winding had little or nothing to do with it. The reason for this may be given as follows:

Fig. 9 represents two main poles and an interpole of a direct-current generator or converter, with their windings in place. The direction of current or polarity of each side of each coil is also indicated by + or —. It is evident that between the interpole and one main pole, the interpole winding and the main field winding are of the same polarity, while on the opposite side of the interpole, these two windings are in opposition. Let A equal the ampere turns of the interpole and B the ampere turns in the main coil. Then, $A+B$ will represent the leakage ampere turns at one side of the interpole and $A-B$ will represent the leakage ampere turns at the other side. Therefore, the leakage at the two sides of the poles is represented by $(A+B)+(A-B) = 2A$; that is, the leakage could be considered as due to the interpole winding entirely and may also be considered as due to double the interpole turns acting as one side of the interpole only. Another way of looking at this is to consider that the windings on the main pole produce leakage in the interpoles, but the leakage due to one main pole acts radially in one direction in the interpole, while that due to the other main pole is in the opposite direction.

Considering therefore the interpole leakage as being due to the interpole ampere turns only, it is evident that the synchronous converter will not be troubled with saturation of the interpoles to the same extent as a direct-current generator. With the same size of interpole it is evident that the converter should be able to carry heavier overloads than the direct-current generator before saturation of the interpoles is reached.

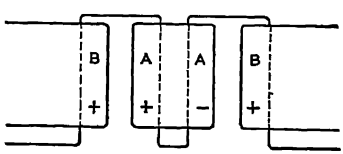


Fig. 9

It was mentioned before that a closed conducting circuit around the interpoles would be objectionable. This has been proved by experience with interpole generators. It is evident from the preceding analysis that the ampere turns on the interpole of a direct-current generator should always rise or fall in

proportion to the armature ampere turns in order to give best commutation, assuming, of course, no saturation of the poles. If the interpole turns are directly in series with the armature winding, with no shunt across the interpole winding, it is evident that the interpole ampere turns must vary in direct proportion to the armature ampere turns. However, if a non-inductive shunt, for instance, were connected across the interpole winding in order to shunt part of the current, then in the event of a sudden change in load, the interpole winding being inductive due to its iron core and the shunt being non-inductive, the momentary division of current during a change in load would not be the same as under steady conditions. In other words, if the armature and interpole current were suddenly increased, then a large part of the increase would momentarily pass through the non-inductive interpole shunt until steady conditions were again attained. In consequence, the interpole ampere turns would not increase in proportion to the armature ampere turns just at the critical time when the proper commutating field should be obtained.

The same condition is approximated when a separate conducting circuit is closed around the interpole. A sudden change in the current in the interpole winding, causes a change in the flux, and secondary currents are set up in the closed circuit, which always act in such a way as to oppose any change in the flux, whereas, the flux in reality should change directly with the current. The above described non-inductive shunt across the interpole winding might be considered also as completing a closed circuit with the interpole winding, and therefore retarding secondary currents would be set up in this closed circuit with any change in the flux in the interpole.

In some cases it may be impracticable to get exactly the right number of turns on the interpole winding to give the correct interpole magnetomotive force. For example, on a heavy current machine, 1.8 turns carrying full current might be required on each interpole. If two turns were used, with the extra current shunted, the right interpole strength would be obtained. A non-inductive shunt, however, is bad, as shown above. However, if an inductive shunt is used, instead of non-inductive, and the reactance in this shunt circuit is properly adjusted, then it is possible to get the right interpole strength for normal conditions and still obtain satisfactory conditions with sudden changes in load. Also, by arranging the interpole winding so that a very considerable percentage of the current

is shunted normally by an inductive shunt having a relatively high reactance compared with the interpole, it should be possible to force an excess current through the interpole winding in case of a sudden increase in load, in case a stronger commutating field were needed at this instant.

On the interpole synchronous converter a non-inductive shunt across the interpole winding should act very much as on an interpole generator and therefore non-inductive shunts are inadvisable. If any shunting is required it should be by means of an inductive shunt in those cases where the current from the converter is liable to sudden fluctuations, as in railway service. Where the service is practically steady, a non-inductive shunt should prove satisfactory for the interpoles of converters or direct-current generators.

Under extreme conditions of overload current, that is, in case of a short circuit across the terminals, it is questionable to what extent interpoles are effective. It is practicable to design interpoles on direct-current generators which will not unduly saturate up to possibly three or four times normal load. However, in case of a sudden short circuit the current delivered by the machine is liable momentarily to rise to a value anywhere from 15 to 30 times full load current. With this excessive current the interpoles of the direct-current generator must necessarily be more or less ineffective. On account of saturation, the commutating flux under the interpole cannot rise in proportion to the current. However, there should still be some commutating field present, which condition is probably considerably better than no field at all, or a strong field in the opposite direction as would be found without commutating poles. Therefore, in direct-current generators with well-proportioned interpoles, the conditions on short circuit are generally less severe than in non-interpole machines.

If the pole is highly saturated by the heavy current rush on short circuit, then it is evident that a highly inductive shunt, as described above, which would increase the interpole current in a greater proportion than the armature current, would simply mean higher saturation with little or no increase in the useful flux under the interpole.

In the synchronous converter at short circuit the conditions may be somewhat different. When the converter is short circuited it can also give extremely high currents, possibly much greater than the corresponding direct-current generator can give.

Both the armature winding tied to an alternating-current supply system, and the presence of the low resistance dampers on the field magnetic circuit, tend to make the short circuit conditions more severe in the converter. The worst condition, however, would appear to be in the relation of the interpole ampere turns to the armature ampere turns on short circuit. As shown before, the normal ampere turns on the interpole winding will be only 25 per cent to 40 per cent of the direct-current ampere turns on the armature. In the case of a sudden short circuit the armature momentarily may deliver a very considerable current as a direct-current generator, and the armature reaction, or the resultant magnetomotive force, may approach that of a direct-current generator. In such case the ampere turns on the interpole will be very much smaller than the armature resultant magnetomotive force at this instant and thus there will be no commutating flux under the interpole, but, on the contrary, the armature being stronger, there will be a reverse flux which may be considerably higher than if no interpole were present, as the iron of the interpole represents an improved magnetic path for such flux. While the converter armature will probably never deliver all its energy as a direct-current generator at the instant of short circuit, yet it may be assumed that it will deliver some of its load thus, and it does not require a very large per cent to be generator action in order to neutralize, or even reverse the effect of the interpoles. In consequence, on a short circuit the converter may have a reverse field under the commutating pole, while the direct-current generator under the same condition will have a field of the proper direction but of insufficient strength which, however, is a much better condition than a field of the wrong polarity.

The inductive shunt mentioned before, which normally shunts a considerable portion of the interpole current, might be more effective in a converter than in a direct-current generator in the case of a short circuit. In a direct-current generator, the interpoles would be so highly saturated, as described before, that the increase in current in the interpole winding due to the inductive shunt would be relatively ineffective. In the converter, however, the saturation of the interpole can normally be very much lower than in the direct-current generator and it might be practicable to so proportion these interpoles that they do not saturate highly, even on short circuit. In consequence, a strong inductive shunt might force up the interpole ampere

turns so that the negative field under the interpole would be much decreased, or might even be changed to a positive field and thus become useful in commutation. This would be helpful *only during the short circuit.* However, converters not infrequently flash over or "buck" when the circuit breaker is opened on a very heavy overload or a short circuit and not when the first rush of current occurs. If the flash tends to occur at the opening of the circuit, then the above mentioned inductive shunt might have just the opposite effect from what is desired, for it would tend to develop or maintain a stronger field under the interpole after the armature reaction is removed. In consequence, the heavy inductive shunt might prove harmful in such a case.

Another condition exists in a converter which does not exist in a generator. When a short circuit occurs on a direct-current generator, the armature reaction tends to distort the main field very greatly—so much so that the field of the machine is very greatly weakened. This decreases the terminal voltage and the resultant decrease in the shunt excitation will still further tend to weaken the field. In consequence, the machine tends to "kill" its magnetic field and the voltage tends to drop to a low value. Therefore, when the breaker opens on a short circuit the direct-current voltage may be falling rapidly. When the armature current is removed from the machine the voltage may rise slowly, depending upon the natural rate of building up the field. Consequently, after the breaker opens there is little or no tendency to flash, and practically all difficulties occur during the current rush, before the breaker opens. In a converter, however, the conditions are different. The armature of the converter is tied to an alternating-current supply system which tends to maintain the voltage on the converter. The machine cannot "kill" its field in the same way as the direct-current generator, for the alternating-current system tends to maintain the field by corrective currents which act in such a way as to tend to hold up the voltage. An enormous current may be drawn from the alternating-current system momentarily in case of a short circuit on the direct-current side of the converter. This heavy alternating current may cause a drop in the alternating-current lines, step-down transformers, etc., so that the supply voltage does fall very considerably and the direct-current voltage does drop materially in case of a short circuit. However, the instant the short circuit is removed by opening the breaker, then the

converter at once tends to attain full voltage as the alternating-current supply system tends to bring the armature up quickly to normal voltage conditions. In consequence there may be a relatively heavy current flow in the alternating-current side of the machine, while there is no direct-current flow in the armature Part of this alternating-current flow represents energy in bringing the machine back to a normal condition, and part is purely magnetizing or wattless current. The energy component tends to produce an armature magnetomotive force giving an active field at the point of commutation. This energy component alternating-current flow, however, cannot be corrected by interpoles, as there is no direct current flowing.

A further difference between the synchronous converter and the direct-current generator, in case of a short circuit, lies in the results of field distortion. The enormous short circuit current from the converter with the armature acting partly as a direct-current generator, may very greatly shift or distort the field flux. The dampers on the field poles tend to delay this distortion. Also, after distortion has occurred they tend to maintain the distorted or shifted field so that momentarily after the circuit breaker opens the converter may be operating without direct-current load but with a very badly distorted or shifted field. This also tends to produce sparking or flashing after the direct-current breaker has opened.

Another condition which may affect the action of interpoles on converters, but which does not occur in direct-current generators, is hunting. When hunting occurs in a converter the energy current delivered to the alternating-current side of the converter pulsates, or varies up and down over a certain range, which may be either large or small. At the same time the direct-current flow is apparently varied but little. In consequence, the resultant magnetizing effects of the alternating current and direct current do not nearly neutralize each other at all times. When the alternating-current energy input is least the converter delivers part of its direct-current load as a generator, the stored energy in the rotating armature being partly given up to supplying the direct-current power. In this case the resultant magnetomotive force may be a very considerable per cent. of the maximum direct-current magnetomotive force of the armature winding. Also, the magnetic field under the main poles is distorted or shifted toward one pole edge. The armature necessarily slows down during this operation, the field polarity of all

the poles being shifted toward one pole edge. The position of maximum e.m.f. of the alternating-current end and also the position of maximum alternating-current flow may be shifted to a certain extent also. In consequence, the magnetomotive force due to the alternating-current flow will be shifted circumferentially a certain amount, while the direct-current magnetomotive force cannot be shifted, being fixed in position by the brushes. In consequence, the alternating-current magnetomotive force may not be in direct opposition to the direct-current at this instant, and the resultant magnetomotive force may be much higher than at normal condition. A moment later the swing may be in the opposite direction; that is, the alternating armature current may be greater than direct current and the energy being received from the alternating-current system is considerably greater than is given out by the direct current. Again, the two magnetomotive-forces will not nearly neutralize each other and there also will be field distortion, but in the opposite direction, and again, the two magnetomotive forces will not be in direct opposition to each other circumferentially. If hunting is very severe, the resultant magnetomotive force of the armature due to the inequality of the input and output, and to the circumferential shifting of the magnetomotive forces with respect to each other, may vary enormously and may pass from positive to negative values periodically. It is evident that under such condition the presence of an interpole may give much worse results than if no interpole were present; for, as mentioned before, if there is a magnetomotive force in the wrong direction at the interpole, the interpole magnetic circuit apparently makes conditions worse. In consequence, an interpole synchronous converter should be especially well designed to avoid hunting.

All of the above considerations have taken into account only the energy currents delivered to the alternating-current side of the converter. Some consideration should be given to the effect of wattless currents in connection with interpoles.

As is well known, when a synchronous converter has its field strength improperly adjusted for the required alternating-current counter e.m.f., alternating currents will flow in the armature in such a way as to correct the effect of the improper field strength; that is, if the field is too weak wattless currents will flow in the armature which tend to magnetize the field of the converter. These currents will be leading in the armature, but will be lagging with respect to the line. On the other hand, if the converter

field is too strong, these wattless or corrective currents will tend to weaken the field and will lag with respect to the armature, but will lead with respect to the line. These corrective currents will have a lead or lag of 90 deg. with respect to the energy currents. Their magnetomotive forces also will have a lead or lag of 90 deg. from the magnetomotive force of the energy component of alternating-current input. As this latter practically coincides with the direct-current magnetomotive force, which is midway between the main poles, the corrective armature currents will have a maximum magnetomotive force practically under the middle of the main poles and therefore become purely magnetizing or demagnetizing due to such position. Also, being at right angles to the energy component, the magnetomotive forces of the corrective currents will have zero value where the energy component has maximum, and therefore should have no direct effect upon the resultant magnetomotive force midway between the main poles, or under the interpoles if such are used. It might be assumed therefore that the usual wattless or corrective currents, which the converter may carry on account of improper field strength, will have no direct harmful effect on the commutation. However, there are apparently some indirect effects due to this corrective current, for when a converter is operated at a bad power-factor, either leading or lagging, there is generally more trouble at the commutator and brushes than when a high power-factor is maintained.

It has been shown that the maximum possible benefit to be derived from interpoles in neutralizing armature reaction is much less in synchronous converters than in direct-current generators. In direct-current generators and motors interpoles have also been of great advantage, due to variable speed and variable voltage requirements. In synchronous converters, however, the requirement of variable speed is obviously absent and that of variable voltage very limited. The converter has constant voltage characteristics and variable voltage can only be obtained through the agency of such relatively expensive devices as induction regulators, synchronous boosters or split-pole constructions. The advantages of interpoles in synchronous converters are then to be looked for only in the direction of increased outputs and higher speeds.

Discussion

Some question has been raised this evening regarding the statements in the paper that in case of sudden overload or short circuit the alternating-current and direct-current magnetomotive forces will not balance each other and that the machine will operate momentarily as a direct-current generator, with a correspondingly high armature reaction. The basis of the criticism is that the converter, being a synchronous machine, cannot change its speed except for a very short period, namely, that occurring within a small fraction of one cycle, otherwise the machine would fall out of step. For such a small change in speed, it was argued, very little energy could be given up as a direct-current generator, as there is not enough stored energy in the converter armature to give up much energy as a direct-current generator without falling out of step.

At first thought, such an argument seemed reasonable, but one answer to it is found in the operation of a synchronous converter on a single-phase circuit. In such operation the energy supplied to the alternating current end *falls to zero twice in each cycle, while the direct-current output remains practically constant.* The alternating-current input must therefore vary from zero to far above the direct-current output of the machine. The converter must therefore act as a direct-current generator, for a brief period, twice during each cycle. When it is considered that such a converter can operate with more or less sparking up to three or four times full-load current, or even much more, depending upon the design of the machine, it is obvious that the converter can deliver very heavy outputs momentarily as a direct-current machine without falling out of step.

Also, a little calculation will show that with an ordinary design of synchronous converter the stored energy in the armature is such that, in dropping back as much as 45 electrical degrees in position, the armature could give up an enormous energy compared with its normal rated capacity. If it were not for this it would not be possible to run the machine on heavy load on a single-phase circuit.

That is all I will say in regard to the points brought up in the discussion. However, there are several points I want to bring out in connection with the paper itself. In the first part of the paper it is stated that the ampere turns on the interpoles of a direct-current generator are always greater than the ampere

turns of the armature winding. This statement is not correct in all cases but in those arrangements which depart from this rule, direct-current generators and converters would be affected in the same way so that for comparative purposes the statement in the paper may be considered as correct.

When there are as many interpoles as there are main poles it is correct to say that the ampere turns on the interpoles should always be greater than on the armature. However, in some cases, especially on small machines, the number of interpoles on direct-current machines is made only half as great as the number of main poles. There are several advantages in this arrangement and they apply equally well to generators and synchronous converters. Obviously where only half as many interpoles are used the commutating flux or field of each interpole must be at least twice as strong as when the full number of interpoles is used. as the opposing e.m f. set up by the interpoles must be sufficient to overcome the e m.f. of self-induction, regardless of the number of interpoles. This opposing e.m.f. need not be distributed over the whole armature coil, but could be located over either side of the commutated coils or even along a short portion of its length. It is only necessary that this opposing e.m f. should have the proper value, while the distribution of it seems to be of relatively less importance. It should be understood, however, that the use of half the interpoles is permissible only with drum-wound armature windings, where each armature coil spans approximately one pole pitch. Ring-wound armatures require the full number of interpoles.

Experience shows that when but half the number of interpoles is used the demagnetizing ampere turns, or those which directly oppose the armature magnetomotive force, should have about the same value *per interpole* as when the full number is used. However, the effective ampere turns which set up the commutating flux must be doubled in value, as just stated. Therefore the total ampere turns *per interpole* would be greater than when the full number of interpoles is used, but the total number of ampere turns on all the interpoles is much less than with the full number of interpoles. In consequence, there is a very considerable saving in the amount of copper required.

On account of the increased number of ampere turns per interpole when half the number of poles is used, the interpole leakage will be increased in proportion. This is particularly

objectionable on large machines where the design of the interpole becomes difficult on account of magnetic leakage. Therefore this arrangement is usually confined to small machines.

A very considerable advantage in this arrangement is that the ventilating conditions are improved due to the fact that the interpoles and main poles do not so completely enclose the armature, for, with alternate interpoles omitted, the circulation of air between the armature and the field poles can be materially improved.

With interpole converters, with their smaller ampere turns per interpole, the omission of alternate interpoles will not have as much influence on the general design as in the case of direct-current generators. As the interpole ampere turns are only about 35 per cent. as great as on a direct-current machine, and as about half is useful and half demagnetizing, it is evident that the useful component would readily be doubled, thus doubling the useful flux, while the total leakage would still be far less on a direct-current machine. Therefore the smaller number of interpoles is much better adapted to the synchronous converter than to the direct-current generator.

In the converter the use of the small number of interpoles also possesses a further advantage. In the case of a short circuit, and assuming a negative field to be set up by the armature reaction, as described in the paper, the use of half the number of interpoles would cut this reverse field to half value. In consequence, any flashing tendency would be proportionately reduced. Half the neutral spaces being without interpoles, and the other half having interpoles, it is evident that such an arrangement should be practically midway between a non-interpole and a full interpole converter as regards any flashing tendencies.

It is also evident that with half the number of interpoles the ventilating conditions will be improved just as on the direct-current generator.

The lower leakage in the interpoles of the converter allows another material difference between the design of the converter interpoles and those of the direct-current generator. In ordinary direct-current generators, especially those of large capacity, the interpoles, as a rule, are made almost the full width of the armature core, principally in order to maintain a lower saturation of the interpole core. As the width of the interpoles is

varied the leakage flux varies practically in proportion to the width, but the total useful flux remains practically constant. Therefore, with wider interpoles the flux density due to the combined leakage and useful fluxes will be lower than if a narrower pole were used, and the saturation will be correspondingly reduced. In the interpole converter, however, the leakage flux being so much lower than in a direct-current generator, it is evident that the useful flux could be correspondingly increased while maintaining no higher saturation than on a direct-current machine. This, therefore, permits a much narrower interpole on the converter than on a direct-current machine. As the interpole becomes narrower than the armature the reverse field which may be set up on short circuit also should be proportionately reduced, so that with interpoles of practically half the width of the armature, the conditions should be practically equivalent to those where half the number of poles is used, as far as flashing conditions are concerned The use of narrow interpoles should also allow better ventilation than when the full width is used. Narrower interpoles, of course, allow considerably less copper for the same total number of ampere turns However, unless the interpoles can be made less than half the width of the armature, the amount of copper required for this arrangement would be still greater than would be required with only half the number of interpoles, each of full width of the armature.

There are many other points in connection with the use of interpoles on converters which were not mentioned in this paper. I will describe briefly a few interesting features which are encountered in the design of such machines, but which are not found in direct-current machines.

One of these concerns the application of dampers to interpole converters. It is found that the usual distributed cage type of damper supplied with self-starting converters is not directly applicable to the interpole converter Dampers are supplied to synchronous converters for two purposes, namely, to prevent hunting and to obtain good self-starting conditions. To prevent hunting the damper should be thoroughly distributed through and around the pole face in the form of numerous low resistance bars or rods which are joined together at each end by low resistance connectors. There may or may not be any connection between the dampers on adjacent poles. In practice, with well

proportioned dampers, such connection between the poles may be of some benefit, but this is difficult to determine as far as hunting is concerned. Those conductors embedded in the pole and immediately surrounding it appear to give all the damping action which is necessary if the damper is well proportioned.

However, when it comes to self-starting converters, that is, those which are started and brought up to speed by direct application of alternating-current to the collector rings, it is claimed by some designers that the interconnection between the adjacent dampers is of benefit at the moment of starting, by reducing the tendency toward dead points or points of very low starting torque. When started in this manner the armature of the converter becomes the primary of an induction motor, while the cage damper in the field poles becomes the equivalent of a cage winding on the secondary of an induction motor. It is claimed that the interconnection between the dampers to form a complete cage allows better polyphase action in the secondary winding. Any beneficial result of this should show in more uniform torque at start, but not to any pronounced extent in the apparent input required to start the converter and bring it up to speed.

When hunting occurs the magnetic field in the main poles is alternately shifted or crowded toward one pole edge or the other and the parts of the damper embedded in and immediately surrounding the pole face are particularly effective in preventing such shifting. Also, the lower the resistance and the better distributed this damper, the more effective it appears to be in general as regards damping.

On the other hand, for self starting, the damper, acting as a cage secondary of an induction motor, will have the characteristics of such secondary and therefore for best and most uniform starting torque conditions, a relatively high resistance is desirable and a continuous cage is usually preferred. In consequence, the two conditions of best damping and best starting are, to a certain extent, opposed to each other.

In the use of a continuous cage damper is found a difficulty in the application of interpoles to the synchronous converter. If adjacent dampers are connected together, as shown in Fig. 1 then the interpole between the two main poles is actually surrounded by the low resistance damper circuit, a condition which is very objectionable, as explained in the paper. Conse-

quently, the usual arrangement of the cage damper for self starting is not advisable on an interpole converter which is subject to sudden fluctuations in load. In other words, the continuous cage damper should not be used, or its design should be modified very considerably, in the case of self-starting converters, which are subject to considerable fluctuations in load in service. If the continuous cage construction is desired, the individual dampers might be connected together by high resistance connectors.

A second interesting point in the design of interpole converters, but not found in direct-current generators, comes up in connection with the copper loss in the tap coils, that is, those armature coils which are tapped directly to the collector rings. As is well known to those familiar with synchronous converter design, the copper loss in the tap coils of a rotary is relatively high compared with the average loss in all the coils, the loss per coil falling off to a minimum value between the taps. The real limit in carrying capacity of the armature is fixed by the heating of the tap coils and not by the armature copper as a whole. It is possible to overload an armature so that the tap coils will roast out while the remaining coils will show very much less signs of heating. The heating in these tap coils also increases rapidly as the power-factor of the alternating-current input is decreased, the output remaining constant. Therefore by reducing the power-factor of a converter while keeping the direct-current output constant it is possible to roast out the tap coils. The true limit of heating in a converter armature therefore is found in these coils. Herein is found a difference between the interpole and the usual non-interpole converter. In the non-interpole type, as usually constructed, the armature coils are of the fractional pitch or "chorded" type in which the "throw" or "span" of a coil is one or more slots less than the pole pitch. The primary object of this is to improve commutation. In the ordinary direct-current winding there are two coils in each slot one above the other. With a full pitch winding, when the upper coil is being commutated or reversed the lower coil in the same slot is also being reversed so that the e.m.f. of self-

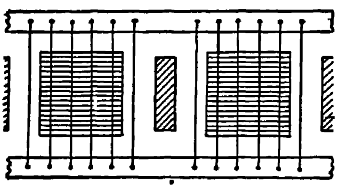


FIG. 1

and mutual-induction of the commutated coils is due to the reversal of the local field of both upper and lower commutated coils in the slot. With a fractional pitch winding, the upper coil which is being commutated lies in a different slot from the lower one which is being commutated at the same instant.

This same arrangement of fractional pitch winding puts the upper tap coil in a different slot from the lower one so that the maximum heating does not occur in the upper and lower coils in the same slot, as would be the case if a full pitch winding were used. Therefore, with a fractional pitch winding the heating is somewhat better distributed than in the full pitch winding. However, with interpoles, a full pitch winding would naturally be used, as a fractional pitch winding would mean a relatively wide interpole with a corresponding increase in distance between the main poles. Therefore with the full pitch winding used with interpole converters the heating due to the tap coils will be more concentrated than in the non-interpole type. In other words, the machine will have less maximum capacity unless more copper is used in the armature coils, or an inferior type of interpole construction is used in order to allow a fractional pitch winding. This looks like a minor point, but when it is borne in mind that in modern converter designs the starting point in the design of the armature winding is the permissible copper loss in the tap coils, and not the armature copper loss as a whole, the importance of this point may be seen.

A third point, not mentioned in the paper but which concerns design as well as operation, is found in self-starting converters. In such machines the alternating current is applied directly to the alternating-current end of the converter and a rotating magnetic field is set up, just as in the primary of an induction motor. This field travels around the armature at a speed corresponding to the frequency of the supply circuit and the number of field poles and all the armature coils in turn are cut by this traveling field. Those coils which are short circuited at the commutator by the brushes form closed secondary circuits and secondary currents are set up by the alternating field just as in commutating type alternating-current motors at start. As soon as the converter gets in motion the short circuit is transferred from coil to coil but the short circuit current must be broken as each coil passes out from under the brushes and this results in more or less sparking, depending on the size and general proportions of

the machine. It is a question to what extent this sparking is dependent upon the normal commutating characteristics of the armature winding. Other things being equal, presumably the better these characteristics the less should be the sparking and burning at the brushes when the converter is self started from the alternating-current end. On this basis then, a converter armature designed with poor commutating characteristics and in which the commutation at synchronous speed is accomplished by interpoles, should spark considerably more when starting than a converter which has inherently very much better commutating characteristics. The presence of commutating poles should in no way help commutation at start as there is no current in the interpole winding. However, as converters are started very infrequently, such increased sparking at start would probably do but little real injury. This is simply mentioned as one of the points in which the designer is concerned.

Some reference has been made this evening to the split pole converter in connection with interpoles. Some distinction should be made between the true interpole or commutating pole arrangement referred to in this paper and what is sometimes referred to as the interpole in the so-called "split-pole" converter. In the split pole converter, as usually built, there is a series of wide poles alternating with narrow poles, the field construction therefore resembling somewhat the ordinary interpole machine. In the split pole converter, however, the small pole is used primarily for the purpose of obtaining variations in the direct-current voltage and not for the purpose of obtaining a true commutating field. The winding on this small pole on the split pole machine is usually in shunt with the armature instead of in series, and its circuit is so arranged that the polarity can be varied from maximum down to zero and to maximum in the opposite direction regardless of the armature current carried. In certain combinations this arrangement can be made to have the effect of commutating poles, but under other conditions it may have just the opposite effect.

The small pole is usually placed close to one of the main poles, thus allowing a fairly wide interpolar space between itself and one of the adjacent large poles and a very narrow space to the other large pole. Commutation occurs usually in the wider interpolar space and not under the small pole itself as is the case in the true interpole machine. The direct-current e.m.f. is

generated by the resultant field due to one large pole and the small pole which is closest to it. When these two have the same polarity the direct-current e m.f. is highest and when they are of opposite polarity it is lowest. However, the alternating-current e.m f. is due to the flux of two adjacent poles, a large and a small one of like polarity. It is evident therefore that the maximum alternating-current e.m.f. will coincide in position with the direct-current only at the highest direct-current e.m.f.; that is, when both fluxes included in one direct-current circuit are of the same polarity. At lowest direct-current e.m.f. when one direct-current circuit includes two fluxes of opposite polarity, it is obvious that the maximum alternating-current e.m.f. must be shifted circumferentially with respect to the direct-current. The alternating-current magnetomotive force will also be shifted in like manner with respect to the direct-current and the resultant of the two will vary both in height and position with variations in the strength and direction of the flux of the small pole.

At highest direct-current e.m.f. a coil which is being commutated lies midway between poles of opposite polarity and the conditions resemble those in an ordinary converter as regards commutation. At the lowest direct-current e.m.f. the commutated coil lies midway between two poles of like polarity and there will be a field flux in the interpolar space in which the armature coil must commutate. The direction of this field may be such that it will assist in commutation; that is, it will tend to overcome the higher magnetomotive force of the armature currents resulting from the alternating-current and direct-current magnetomotive forces being shifted with respect to each other, as just mentioned. Therefore this interpolar field flux may act in a very beneficial manner under certain conditions. However, if this flux is in the right direction for assisting commutation when transforming from alternating-current to direct-current, it will evidently be in the wrong direction when operating from direct-current to alternating-current. Also, this field flux in the interpolar space will vary with any variations in the strength of the small pole; that is, with any change in the direct-current voltage, although the currents in the armature may be unchanged. Also, this interpolar field may remain of constant strength, while wide changes may occur in the armature currents, and thus in their resultant magnetomotive forces. It

is obvious therefore that this interpolar flux can be equivalent to a true interpole of proper strength and polarity, only under a very limited range of operation.

In conclusion I may say that, as brought out in the paper, the real field for interpoles in synchronous converters is found in connection with higher speeds and large outputs per pole. I am an advocate of the highest speeds which the public will stand, up to the point where no further real gain in cost and performance is obtained. If this highest speed in converters is such that interpoles are of material benefit, then in such machines we may look forward to the use of interpoles. However, for the relatively low speeds represented by much of our present practice the use of interpoles can be considered as only a relatively small improvement, concerning which there may be honest differences of opinion regarding the commercial value.

THEORY OF COMMUTATION AND ITS APPLICATION TO COMMUTATING POLE MACHINES

FOREWORD—This paper was the result of many years of the author's work on the subject of commutation. In its presentation, it embodies a new method of looking at the problem. In this method, the armature winding, as a whole, is considered as setting up a magnetic field in the so-called neutral zone; and it is, primarily, the e.m.fs. set up by the armature conductors cutting this field, which are dealt with in this theory of commutation. Before the completion of the paper, the commutating constants of many hundreds of direct-current machines of various kinds were checked to determine the correctness of the method. The paper was presented at a meeting of the American Institute of Electrical Engineers, October, 1911.

Throughout this paper, it will be noted that the term "interpole" was used in place of the present accepted term "commutating pole" which came later.—(Ed.)

IN the usual theory of commutation it is considered that, when the current in a coil is commutated or reversed, the local magnetic flux due to the current reverses also, and in so doing sets up an e.m.f. in the coil which opposes the reversal. This is the so-called reactance voltage referred to in commutation problems. The fact that two or more coils may be undergoing commutation at the same time involves consideration of mutual as well as self-induction. The relation of the mutual to the self-induction, the probable value of each, etc., lead to such mathematical complication in the analysis of the problem, that empirical methods have become the usual practice in dealing with commutation. The usual analytical methods do not permit a ready or easy physical conception of what actually takes place.

According to the usual theory, during the commutation of the coil the local magnetic flux due to the coil is assumed to be reversed. However, in the zone in which the commutation occurs, certain of the magnetic fluxes may remain practically constant in value and direction during the entire period of commutation.

The fact of part of the flux in the zone of commutation remaining practically constant in value and direction, led the author to a method of dealing with the problem of commutation which is based upon consideration of the armature flux as a

whole, as set up by the armature ampere turns. The results obtained by the method were very satisfactory, and it was apparent that a much better conception could be obtained of some of the phenomena of commutation than was possible with former methods.

In the following pages the method is indicated in general, and its application to interpole machines is then worked out in greater detail. In non-interpole machines the problem is greatly complicated by the presence of local currents under the brushes which modify the distribution of certain of the armature magnetic fluxes, as will be shown.

This theory of commutation, with the method of calculation, is based upon the broad principle of the *armature conductors cutting across the magnetic field set up by the armature winding and thereby generating an e.m.f. in the short circuited coils which is proportional to the product of the revolutions, the flux which is cut and the number of turns in series.* The usual "reactance" voltage due to reversal of the local flux of an individual coil is not considered, although its equivalent appears under another form.

The method in general is therefore the same as that used for determination of the main armature e.m.f., except that the magnetic fluxes cut by the armature conductors are those due to the armature magnetomotive force instead of those due to the field.

When the armature winding is carrying current its magnetomotive force tends to set up certain magnetic fields or fluxes which have a definite relation to the position of the brushes. Considered broadly, the current after entering the commutator or armature winding, at any brush arm, divides into two paths of opposite direction. As the winding on each of these paths is arranged in exactly the same way, and as the currents flow in opposite directions, the armature windings in these two paths have magnetomotive forces which are in opposite directions. The resultant armature magnetomotive force rises to a maximum at points corresponding to the brush positions. Midway between these points the magnetomotive force is zero. Magnetic fluxes are set up by these magnetomotive forces, which are a function of the force producing them, and the proportions, dimensions and arrangement of the magnetic paths; and these magnetic fluxes will be practically fixed in position corresponding to the brush setting.

The armature conductors cutting across these fluxes set up by the armature magnetomotive forces, will have e.m.fs. generated in them. In those conductors which have their terminals short circuited by the brushes, these e.m.fs. may be called the short circuit e.m.fs.

There are three principal armature fluxes which are cut by the short circuited armature coils. In the order of their usual importance these are,

1. That which crosses from slot to slot. It may be called the slot flux.
2. The interpolar flux which passes from the armature surface to the neighboring poles or yoke surface. It may be called the *interpolar* flux, as distinguished from *interpole* flux, which term will be used later.
3. That flux set up in the armature end-winding in the zone of the short circuited coil, due to the magnetomotive force of the end windings as a whole. It may be called the end flux.

The short circuited armature coils cutting across these three fluxes generate the short circuit e.m.fs. The whole problem of commutation may be considered as depending upon the predetermination of these three fluxes.

Consider, first, an armature conductor approaching the point of current reversal or commutation. Under this condition the current carried by the coil *always flows in the same direction as the e.m.f. generated by the conductor cutting across the magnetic field or flux set up by the armature winding is induced.* When the terminals of an armature coil pass under the brush and are short circuited, it is obvious that the e.m.f. set up in the coil by the armature flux is unchanged in direction for the coil is still cutting a field of the same polarity. This e.m.f. tends to maintain the current in the short circuited armature coil in the same direction as before but the value the current attains will be dependent upon the short circuit e.m.f. and largely upon the resistance in the circuit, which will usually consist of the resistance of the coil itself and of the brush contact. As the coil passes out of short circuit, that is, as it leaves the brush, the current must flow in the opposite direction, but the e.m.f. set up by the armature flux is still in the same direction as before. Therefore, after commutation, the armature current in the coil is flowing in opposition to the e.m.f. set up in the coil by the armature flux.

The following is a method for calculating approximately the three fluxes before described and the e.m.fs., generated by the

armature conductors cutting them. The interpolar fluxes will be considered first, the end fluxes second, and the slot fluxes last, as these latter are greatly complicated by the problem of local currents produced largely by the interpolar and end fluxes.

Interpolar Armature Flux

By this is meant the flux in the interpolar space between the armature core and the field poles and yoke, due to the magnetomotive force of the armature winding, as shown in Fig. 1. This magnetomotive force has its highest value at those parts of the armature winding corresponding to the brush contacts on the commutator and is zero midway between such points. If the brushes are set with zero lead then the maximum magnetomotive force of the armature lies midway between adjacent field poles and will taper off in value from this midpoint toward the

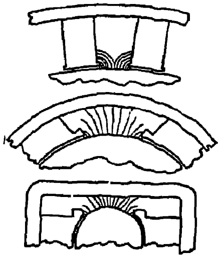


Fig. 1

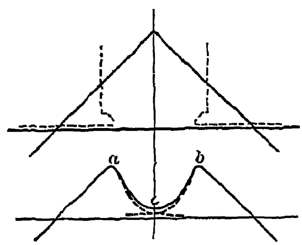


Fig 2

adjacent edges of the poles. The flux density between the armature surface and the sides of the poles should therefore tend to taper off as the armature magnetomotive force is reduced but, in most types of field construction, it tends to increase in value due to the relatively shorter magnetic path as the edges of the poles are approached. Usually this increase very considerably overbalances the decrease due to the lower magnetomotive forces and in consequence the interpolar flux density due to the armature generally has a minimum value midway between the poles and rises toward the edges of the poles. This is illustrated by Fig. 2.

The density of this flux in the interpolar space is dependent upon many conditions such as the ampere turns of the armature winding per pole, distance between poles, conformation of the poles, yoke, etc. In Fig. 2 the ordinates of the dotted lines represent the flux densities at the armature interpolar surface

due to each of the two adjacent poles. The resultant of these two is the full line *a c b* which represents the distribution of the armature interpolar flux. This interpolar flux might be considered as a true magnetic field fixed in space with respect to the position of the brushes. This field being fixed and the armature conductors rotating it is obvious that any conductor moving across this magnetic field must have e.m.f. generated in it, the value of which depends upon the flux which is cut at any instant. Therefore, the e.m.f. due to this interpolar field can be determined directly, if the intensity of the field itself can be calculated.

During the period of commutation the armature coil is short circuited and has the current reversed in it under certain portions of this field. The problem is to determine the strength of the field corresponding to this point of commutation and then by direct calculation the corresponding e.m f. can be determined. In the following analysis two cases will be considered, namely, pitch windings, and "chorded" or "fractional pitch" windings.

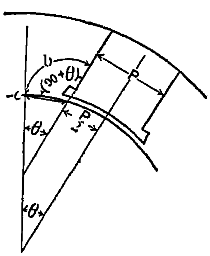


FIG. 3

Pitch Windings. When commutating or reversing a coil with a pitch winding it is evident that if there were no lead at the brushes such a coil would commutate, on the average, at the midpoint between two poles. The e.m.f. generated in the coil by cutting the interpolar field would therefore be proportional to the strength of the interpolar flux at the midpoint. This flux can be determined approximately in a fairly simple manner in the ordinary types of machines in which the poles are relatively long compared with the distance between adjacent pole tips and where the distance from the armature surface to the yoke is relatively great. The following is a method which appears to give reasonably close results:

Let W_t = total number of wires on the armature.

I_c = the current per conductor.

p = number of poles.

Then, the armature ampere turns per pole $= \frac{I_c \times W_t}{2p}$, neglecting any change in ampere turns due to the short circuiting action of the brushes.

In Fig. 3 let b represent the length of the mean flux path corresponding to the mid-interpolar position. This is assumed

to be a part of a circle which is practically at right angles to the armature surface and the side of the field pole, as indicated in Fig. 3.

Let P = width of body of pole.

Let B_i = the flux density at the midpoint between the poles.

Then $B_i = \dfrac{2 \times 3.19\, I_c \times W_t}{2\, p\, b}$.

But $b = 2\,\pi\, a\,\dfrac{(90+\theta)}{360}$, approximately, as angle $(90+\theta)$ is only approximate.

Or $b = 2\,\pi\, a\left(0.25+\dfrac{\theta}{360}\right) = 2\,\pi\, a\left(0.25+\dfrac{1}{2\,p}\right)$.

Also, $a = \left(\dfrac{\pi\, D}{2\,p} - \dfrac{P}{2}\right)$ approximately.

Therefore

$$b = 2\,\pi\left(0.25+\frac{1}{2\,p}\right)\left(\frac{\pi\, D - Pp}{2\,p}\right) = \frac{\pi\,(0.25p+0.5)\,(\pi\, D - Pp}{p^2}$$

Therefore

$$B_i = \frac{2 \times 3.19\, I_c\; W_t \times p^2}{\pi\,(0.25p+0.5)\,(\pi\, D - Pp) \times 2\,p}$$

$$\text{Or, } B_i = \frac{I_c\, W_t\, p}{(0.25p+0.5)\;\;(\pi\;\; D - Pp)} \text{ approx.}$$

The above gives the approximate flux density at the midpoint between poles. The flux densities at points at each side of the midpoint can be determined in a similar manner, taking into account the lower armature magnetomotive force as the midpoint is departed from. As the edge of the pole is approached the effect of pole horns may complicate the flux distribution so that the above method of calculating interpolar flux density will not apply for points close to the pole.

E.m.f. Due to Interpolar Flux.

Let E_c = The e.m.f. due to cutting the armature flux.
D = diameter of armature.
L = length of core including ventilating spaces.
T_c = turns per individual armature coil.
R_s = revolutions per second.

Then, the e.m f. induced in a coil cutting the field at c (Fig. 2) can be represented by the formula,

$$E_c = \frac{B_i \times \pi D L \times 2\ T_c \times R_s}{10^8}$$

Or,

$$E_c = \frac{I_c W_t p}{(0.25p+0.5)(\pi D - Pp)} \times \frac{2\pi D L T_c R_s}{10^8}$$

Or

$$E_c = \frac{I_c W_t T_c R_s}{10^8} \times \left(\frac{2p \times \pi D L}{(0.25p+0.5)(\pi D - Pp)} \right)$$

Incidentally, with this method of dealing with the problem the effect of the addition of an interpole can at once be seen. The magnetomotive force of the interpole is superimposed on that of the armature and the resultant flux is then considered. The armature conductors cut this flux and thereby generate e.m.f. If the interpole magnetomotive force is stronger than that of the armature, then the flux established will be in the opposite direction in that part of the armature face which lies under the interpole. Therefore, the flux or field over the commutated coil in the non-commutating pole machine is replaced by flux in the opposite direction. The presence of the interpole does not increase the reactance of the armature coil as sometimes considered, but, on the contrary, the harmful flux is replaced by one which is of direct assistance in commutation.

Effect of Brush Width. In cutting across the interpolar flux it is obvious that the e.m.f. set up in the short circuited coil is not a function of the length of time the coil is short circuited, for this interpolar flux is set up by the armature winding as a whole and not by individual coils. If two or more armature coils in series are short circuited by the brush, then their e.m.fs. will be in series while the total resistance in the path will be very little higher than in the case of a single coil short circuited, for the principal part of the resistance lies in the brush contact. It is evident therefore that considerably higher short circuit currents can be set up by the interpolar field when more commutator bars, and more turns, are short circuited. It can therefore be assumed that, as far as the interpolar field is concerned, the more

commutator bars the brush covers the greater will be the short circuit current and the greater will be the difficulty in commutation, assuming there is no external field assisting commutation

Chord Winding. With a pitch winding, with no lead at the brushes, the commutation of a coil will occur in the lowest part of the armature interpolar flux, as *a a* in Fig. 4. With a chorded winding, as indicated at *b b*, the commutation will occur under somewhat higher flux than with a pitch winding. Therefore in considering the interpolar flux a full pitch winding commutates under better conditions than a chorded winding.

END FLUXES

The armature winding as a whole sets up certain fluxes in the end windings. These fluxes are fixed in position with respect to the brushes, and the armature coils, in cutting across, them, generate e.m.fs. The only part of these end fluxes concerned in

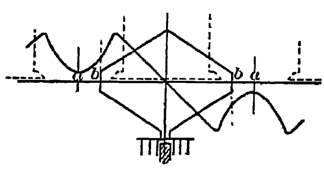


FIG. 4

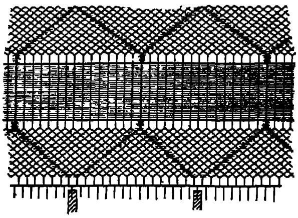


FIG. 5

the present problem is that which the commutating coils cut during the operation of commutation.

Fig. 5 illustrates an armature winding in which the heavy lines represent two coils in contact with the brushes and therefore at the position of commutation. It is only the end flux density along the shaded portion or zone of this diagram which need be considered. If the various densities for this zone can be determined, then the e.m.f. in the commutated coil can be calculated. Only the usual cylindrical type of end windings will be considered, as practically all direct current machines at the present time use this type. Such windings are usually arranged in two layers, the coils of which extend straight out from the armature core for a short distance, usually $\frac{1}{2}$ in. to $1\frac{1}{2}$ in., depending upon size and voltage of the machine, and then extend at an angle to the core of 30 deg. to 45 deg. The conductors of the upper and lower layers therefore usually lie almost at right angles to each other

Pitch Winding Let Fig. 6 represent a single coil of the end winding located in the commutating zone. Both theory and test show that the maximum flux density in this zone is at a and tapers off slightly to b, then tapers off more rapidly from b until it reaches practically zero value at c. It may be assumed with but little error that the decrease from b to c is at a practically uniform rate. The flux density along the commutating zone of the end winding may therefore be represented by Fig. 7, in which the ordinates represent flux density. On the above assumption the total flux in the commutating zone of the end winding can be determined with sufficient accuracy if the density at b, for instance, can be determined and the distances $a\,b$ and $c\,d$ in Figs. 6 and 7 are known. These latter can be determined directly from the winding dimensions.

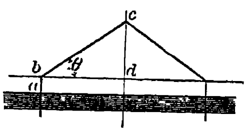


FIG. 6

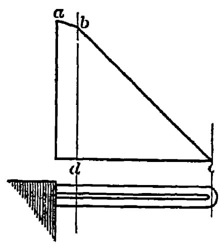


FIG. 7

The following is an approximate formula for the flux density at b, including allowance for proximity of iron end plate, core, etc.

$$B_e = \frac{2.15 \cdot I_c\, W_t \times \log 2\,N}{\pi\, D \sin\theta}$$

N = number of slots per pole.
I_c = current per conductor.
W_t = total armature wires.
D = diameter of armature.
Let $a\,b = h$, and $c\,d = m$.

Then the flux cut by one conductor at one end is

$$\pi\, D\left(h+\frac{m}{2}\right)\times\frac{2.15 \cdot I_c\, W_t \times \log 2\,N}{\pi\, D \sin\theta}$$

Therefore the e.m.f. per single turn of the armature winding,

due to the end flux, considering the end fluxes for both ends of the core, becomes

$$E_c = 2\left(h+\frac{m}{2}\right)\times\frac{2.15\ I_c\ W_t\times\log 2\ N}{\pi\ D\ \sin\theta}\times\frac{\pi\ D\ R_s\times 2\ T_c}{10^8}$$

Or,

$$E_c = \frac{I_c\ W_t\ T_c\ R_s}{10^8}\times\frac{4.3\ (2\ h+m)}{\sin\theta}\times\log 2\ N$$

This formula is on the basis of non-magnetic paths around the end windings, that is, with no bands of magnetic material and no magnetic supports under the coils. The effect of bands over the end winding is approximately equivalent to cutting the flux path to half length for those parts of the end winding covered by the bands. Therefore, with bands, the diagram representing flux density in the commutating zone of the end winding would be as indicated in Fig. 8. In this case the total flux corresponds to the total area of the curve including the dotted portion Of course the actual flux distribution would not be exactly as shown in this diagram for there would be some fringing in the neighborhood of the bands The diagram simply serves to illustrate the general effect of magnetic bands and an approximate method of taking it into account.

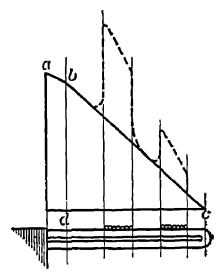


FIG. 8

The effect of a magnetic coil support will be very similar to that of a steel band in reducing the length of path and therefore increasing the flux in the neighborhood of the coil support. However, in case of magnetic bands over the winding and coil supports under it the limit lies in saturation of the bands themselves. This usually represents a comparatively small total flux. The coil support, however, would probably not saturate in any case.

The above formula for end flux can therefore be corrected for magnetic bands and coil supports by multiplying by a suitable constant to cover the increased flux.

It is obvious that the determination of the end flux is, to a certain extent, a question of judgment and experience. No

fixed method or formula can be specified for all types of machines, for this flux would be influenced very greatly by the bands, if of magnetic material, and by the material, size and location of the coil supports and their relation to the bands. Also, eddy currents may be set up in the coil supports which will influence the distribution of the end flux in the zone of the commutated coil. However, in each individual case an approximation can be made which will, in general, be much closer than would be obtained from any empirical rule or by neglecting the effect of the end flux altogether.

Chord Winding. The effect of chording the armature winding is to slightly diminish the flux density in the commutating zone which results in a slight reduction in the e.m.f. of the commutating coil. But a relatively much greater gain is obtained by the consequent shortening of the distance $c\,d$ in Fig. 8 and the corresponding reduction of the total end flux. Due to the chording itself the flux density at b is reduced practically in the ratio of $\frac{\log 2\,N_1}{\log 2\,N}$, where N_1 = number of slots spanned by the coil. For example, if the full pitch is 20 slots and the coil spans 18 slots, then the density at b will be reduced in the ratio of $\frac{\log 36}{\log 40} = 0.971$ due to the chording itself; and the flux along $c\,d$, Fig. 7, will be further reduced in the ratio of $\frac{18}{20}$ due to the shorter end extension. The average flux along $c\,d$ therefore will be reduced to $0.9 \times 0.971 = 0.874$, or about 87 per cent of that of a pitch winding.

Effect of Brush Width. As in the case of the interpolar flux the width of the brush, or the number of armature coils short circuited by the brush, has practically no influence on the e.m.f. generated per turn. However, the total effective armature ampere turns will be reduced slightly, if the average current in the short circuited turns is less than the normal current. This will have a very slight effect on the e.m.f.

Slot Flux

By this is meant the magnetic flux across and over the armature slots which does not extend to the yoke or field poles.

Two general cases will be considered; first, that in which no local currents are present, which is the case in well designed interpole machines; and second, that in which there are local

currents set up in the short circuited coils, which is almost invariably the case in machines without interpoles or some other form of compensation. Also, pitch and chorded windings will be considered.

Slot Flux with No Local Currents

Pitch Winding. Let Fig. 9 represent an upper and a lower coil in the same slot, with equal turns and currents. Then if there is no saturation in the adjacent teeth the flux density across the slot will be zero at the bottom of the lower coil and will rise to a maximum value at the top of the upper coil. There will also be a flux across the slot above the upper coil and also from the top of the tooth as indicated in Fig. 9. The total slot flux entering at the bottom of the teeth is therefore equal to the total flux which crosses the two adjacent slots, plus the flux crossing at the top of the slots. The interpolar flux which ex-

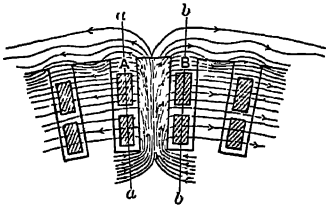


Fig. 9

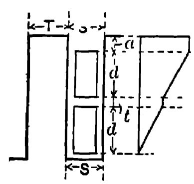


Fig 10

tends from the armature surface to the poles or yoke is not included in this.

As this slot flux is practically fixed in position the armature conductor in slot A, in passing from a to b must cut this flux. It is obvious that the flux which crosses above the uppermost conductor in the slot is cut equally by all the conductors in the slot, as the coil passes from position a to position b; but the flux crossing the slot below the uppermost conductor does not affect all the conductors equally, and therefore, for simplicity of calculation, an equivalent flux of lower value can be used which may be considered as cutting all the conductors equally.

Let d Fig. 10, represent the depth of the conductors of one complete coil.

t represent the distance between the upper and lower coils.

a represent the distance from the upper conductor to the core surface.

s represent the width of the slot, assuming parallel sides.
n represent the ratio of width of armature tooth to the width of the armature slot, *at the surface of the core.*
T_c represent turns per single coil, or per commutator bar.
C_s represent the number of individual coils, or commutator bars, per complete coil.
L represent the width of armature core, including ventilating spaces.
I_c represent the current per armature conductor.

Then, ampere turns per upper or lower coil $= I_c\, T_c\, C_s$.

$$\text{Total flux across coil space} = \frac{3.19\, I_c\, T_c \times C_s\, L\, (2\,d+t)}{s}.$$

$$\text{Flux across slot above coil} = \frac{3.19\, I_c\, T_c\, C_s\, L \times 2 \times a}{s}$$

Flux from tooth top across the slot is approximately,

$$3.19\, I_c\, T_c\, C_s\, L \times 2 \times 0.54\, \sqrt{n}$$

$$\text{Total flux above upper coil} = 3.19\, I_c\, T_c\, C_s\, L\, \frac{(2\,a + 1.08\, s\, \sqrt{n})}{s}$$

The sum of the two fluxes represents the total flux across one slot which enters at the bottom of one tooth. As a similar flux passes across the slot at the other side of the tooth the total flux entering the tooth will be double the above and becomes

$$\text{Total slot flux} = 2 \times 3.19\, I_c\, T_c\, C_s\, L\, \frac{(2\,d + t + 2\,a + 1.08\, s\, \sqrt{n})}{s}$$

This total flux cannot be used directly in the calculations as it does not affect all the conductors equally. It is therefore necessary to determine equivalent fluxes for the upper and lower coils which can be used instead of the above value.

For the lower coil the following value has been calculated:

$$\text{The equivalent flux} = \frac{2 \times 3.19\, I_c\, T_c\, C_s\, L}{s}\, (1.833\, d + t)$$

And for the upper coil,

$$\text{Equivalent flux} = \frac{2 \times 3.19 \times I_c\, T_c\, C_s\, L}{s} \times 0.833\, d$$

To these equivalent fluxes should be added the total flux above the upper coil. This gives the total effective flux for the upper and lower coils. Then, for the lower coil,

Total effective flux

$$=2\times 3\ 19\ I_c\ T\ C_s\ L\left(\frac{1\ 833\ d+t+2\ a+1.08\ s\ \sqrt{n}}{s}\right)$$

And for the upper coil,
Total effective flux

$$=2\times 3\ 19\ I_c\ T_c\ C_s\ L\times\frac{(0.833d+2\ a+1\ 08\ s\ \sqrt{n})}{s}$$

The average value of the effective flux for the upper and lower coils then becomes,

$$3\ 19\ I_c\ T_c\ C_s\ L\ \frac{(2.67\ d+t+4\ a+2.16\ s\ \sqrt{n})}{s}$$

(This average effective value is approximately 80 per cent of the total slot flux.)

On the basis of a pitch winding and the assumption that only one armature coil is short circuited, that is, with the brush covering the width of only one commutator bar, then the above slot flux is cut by all the coils in the slot in passing through one slot pitch. From this the e.m.f in the commutating coil due to the slot flux can be calculated directly and may be expressed as follows

$$E_c=\frac{2\ T_c\ R_s}{10^8}\times\text{number of slots}$$

$$\times 3\ 19\ I_c\ T_c\ C_s\ L\ \frac{(2.67\ d+t+4a+2\ 16\ s\ \sqrt{n})}{s}$$

But $C_s\times$number of slots$=$No of commutator bars

$$=\frac{\text{total number of conductors}}{2\ T_c}=\frac{W_t}{2\ T_c}$$

Therefore the above expression for e.m.f may be changed to the form,

$$E_c=\frac{3.19\ I_c\ W_t\ T_c\ R_s\ L}{10^8}\quad\frac{(2.67\ d+4\ a+t+2.16\ s\ \sqrt{n})}{s}$$

If it is desired to compare this expression with a certain well known formula which has been much used heretofore, then let

the quantity in the parenthesis in the above expression be represented by c_x. The formula can then be changed to,

$$E = (2\times 3.19\times c_x)\times \frac{I_c\, T_c^2 \times \text{number commutator bars} \times R_s \times L}{10^8}$$

It contains the same terms (except in the value of the constant) for the expression of the e.m.f. which has been used heretofore in determining the reactance of the commutated coil.

Effect of Brush Width or Number of Commutator Bars Covered by Brush. The above formulas are on the basis of the brush covering only the width of one commutator bar. In this case all the conductors of one slot cut across the entire slot flux in passing through one tooth pitch. However, if the brush covers more than one commutator bar, then the full slot flux is not cut in passing through one tooth pitch, and a movement greater than one tooth pitch is required for full cutting. For example, if there is one commutator bar per armature slot and the brush covers a width equal to two commutator bars, then the total cutting of the slot flux will take place in two tooth pitches. Again, if there are three commutator bars per armature slot and the brush covers the width of one commutator bar, then the total cutting of the total slot flux would occur in one tooth pitch, while if the brush covered two bars, the total cutting would occur in $1\frac{1}{3}$ tooth pitches; and if it covered three bars $1\frac{2}{3}$ tooth pitches are required. In other words, the total cutting will occur in a period corresponding to the number of commutator bars per slot plus one less than the number of commutator bars covered by the brush.

On this basis the correction factor for the slot e.m.f. should be expressed by the term $\frac{C_s}{C_s+B_i-1}$*, where C_s = number of commutator bars per slot, and B_i = number of commutator bars spanned by the brush. However, with several coils per slot, and with the brush spanning several bars, the rate of cutting of the tooth flux for the entire period is not quite the same as the rate for one tooth pitch. Taking this into account the correction factor should not be equal to $\frac{C_s}{C_s+B_i-1}$, but is slightly greater. Up to four commutator bars per slot, and three bars

*By applying this correction factor, $\frac{C_s}{C_s+B_i-1}$, the average slot e. m. f. for the period of commutation is obtained.

spanned by the brush the correction factor can be expressed by the term $1+\frac{1}{B_i C_s} - \frac{1}{C_s}$.*

Taking the lengthened period of reversal into account, it would appear that a wide brush covering a large number of commutator bars should be beneficial in reducing the e.m.f generated by the slot flux. This is true where the local currents are very small, or are absent, as is the case in a properly designed interpole machine. In a non-interpole machine where the local currents in the short circuited coils may be relatively high, this condition does not hold, as will be explained later.

The above formula for e.m.f. due to the slot flux should therefore be modified by multiplying by a factor which takes into account the period of reversal as affected by brush width.

Chord Winding. The armature winding may be chorded one or more slots and, in some instances, where there are several coils side by side there has been chording of part of the conductors in the slot. In Fig. 11 is illustrated the conditions with one-slot chording The total slot flux now occupies two teeth instead of one. Therefore the e.m.f. set up by cutting across this slot flux will be approximately one-half that which is obtained with a full pitch winding, on the basis of the brush covering the width of one bar only, for the e.m.f generated by cutting this flux will be reduced in proportion as the period of cutting is increased There is one slight difference from the flux distribution with a pitch winding, namely, that at the top of the teeth. With a chorded winding this flux will be slightly greater than with a pitch winding, but the total effect of this difference should be relatively so small that ordinarily the value need not be changed. Therefore equivalent fluxes used with chord windings can be taken the same as for pitch windings. In consequence, the e.m.f. *due to the slot flux*, with one-tooth chording, may be taken as one-half that for a pitch winding, with the brush covering one commutator bar in both cases.

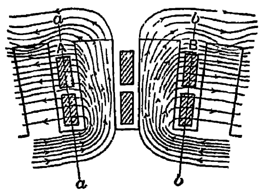


FIG 11

For two-slot chording the slot flux may be considered as occupying the space of two teeth only, while there will be a magnetically idle tooth at the center. The e.m.f. per coil actually generated by cutting the slot flux will be, for part of the period

*General use of this factor, $1 + \frac{1}{B_i C_s} - \frac{1}{C_s}$ should be avoided. It is not applicable to all types or combinations of windings Use instead the factor giving average

the same as for one-slot chording, but there will be an intermediate period where the slot e.m.f. is practically zero, which does not occur with a one-slot chording or with a pitch winding. The average results, however, should be practically the same as if the total slot flux were actually distributed over three teeth instead of two.

Effect of Brush Width with Chord Winding. In the chord winding, when the brush covers two or more commutator bars, the period of cutting the slot flux will be lengthened just as with a pitch winding on the assumption of no local currents For example, if there are three commutator bars per armature slot and the winding is chorded one slot, then with the brush covering one commutator bar, complete cutting of the slot flux will occur in the space of six commutator bars. If the brush covers three commutator bars instead of one, then complete cutting will occur in the space of eight commutator bars, while in a corresponding full pitch winding it would occur in the space of five bars. Therefore, the wide brush represents an improvement with the chorded winding, but not to the same extent, relatively, as with the pitch winding. This is on the assumption of absence of local currents in the short circuited coils. *

Bands on Armature Core. By the preceding method of analysis the effect of bands of magnetic material on the armature core can be readily taken into account. This effect represents simply an addition to the total flux which can pass up the tooth and across the top of the slots. From the ampere turns per slot, the clearance between the bands and the iron core, the total section of the band, etc., the flux due to the band can be calculated This flux can either be combined directly with the slot flux already described and the resultant e.m.f. can then be calculated; or, the e.m.f. can be calculated independently for the band flux alone Magnetic bands on the armature introduce a complication into the general e.m.f. formula due to the fact that in many cases the flux into the bands is such as to highly saturate the band material at relatively low armature currents. This flux therefore is usually not proportional to the armature ampere turns. If the e.m.f. due to the band flux is to be calculated separately, the following formula can be used:

ϕ_b represents the total magnetic flux in the band from the armature core considering both directions from the tooth, then

$$E_c = \frac{2\,\phi_b\,N\,p\,T_c\,R_s}{10^8}$$

*Considering chording, the correction factor $\frac{C_s}{C_s + B_t - 1}$ becomes $\frac{C_s}{C_s + B_t - 1 + K}$ where K = slots chorded $\times\ C_s$. For the general case, where there are P' circuits and P poles, the correction factor becomes $\frac{C_s}{[illegible]}$

This formula holds true for the band flux which passes throug the one tooth in the pitch winding. Proper allowance must be made for the effect of chord windings and brush width, which can be done by the methods already described.

SLOT FLUX WITH LOCAL CURRENTS

Pitch Winding. In the preceding analysis local currents have not been included, as the method would be greatly complicated by taking such currents into account. In the general method given below the effect of local currents in the short circuited coils can be most easily shown.

As already explained, an armature coil, as it approaches the short-circuit condition, has an e.m.f. generated in it by the inter-polar and the end fluxes. After the coil is short circuited this e.m.f. is still generated by the coil and naturally a local or short circuit current tends to flow through the coil, brush contact

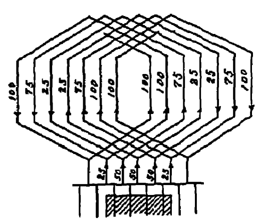


FIG. 12

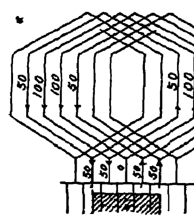


FIG. 13

and brush. In addition, the work, or supply, current is being furnished to the armature winding through the brushes. These two currents are superimposed in the short circuited winding in such a way as to have a very pronounced influence in the distribution of the slot fluxes. This effect can be best seen by first determining the distribution of the work current in the various parts of the short circuited winding on the assumption of *no local current* and second, determining the distribution of the local currents on the assumption of no *work current, but with the same armature magnetomotive force* as in the first assumption. The two distributions can then be combined and the resultant currents in the various parts of the short circuited coils can be obtained.

Let Fig. 12 represent the first assumption in which no local currents are present. In order to illustrate conditions to better advantage, four commutator bars are assumed to be covered by the brush. Uniform distribution of current over the brush contact can be assumed in this case, as there are no local currents.

Tracing out the current in each short circuited coil in Fig. 12, it will be seen that the current decreases at a uniform rate and then rises in the opposite direction at the same rate until the short circuit is removed The period of commutation is the longest possible with this number of commutator bars short circuited, and the brush conditions are ideal, as the current density at the brush contact is uniform at all parts The above are the conditions which the designer endeavors to obtain in the construction of good interpole machines, as will be shown later.

In Fig 13 the same arrangement of winding and brushes is chosen as in Fig. 12 except that only the local currents are shown and the values of these are assumed as proportional to the e.m.fs. in the short circuited coils and the resistance in circuit. In this diagram the current is a minimum in the coils at the moment that short circuit occurs, and rises to a maximum value and then diminishes to zero value again at the end of the short circuit

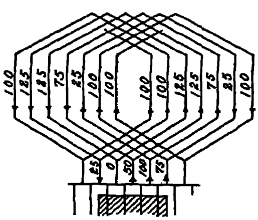


FIG 14

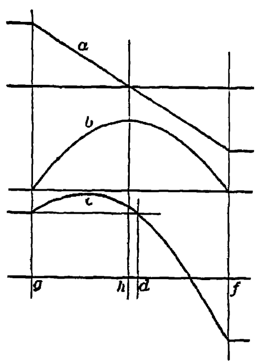


FIG 15

In Fig 14 the currents of Fig. 12 and 13 are superimposed The resultant currents in the various parts of the short circuited winding are seen to rise after short circuit until a maximum value is reached and then decrease rapidly and reverse to normal value in the opposite direction. Therefore, the period from normal value of the current to normal in the opposite direction is very much shorter than when no local currents are present It may therefore be considered that the period of reversal is much reduced by the presence of the local currents, so that the e m.f in the short circuited armature conductors generated by the slot flux is proportionately increased, compared with the value it would have in case the local currents were absent These conditions can be shown possibly in a somewhat better manner by curves *a*, *b* and *c* in Fig. 15 The curve *a* shows the distribution of current in the short circuited coils without any local currents Curve *b* shows the distribution of local currents

while curve *c* shows the resultant of the two. The distance between *d* and *f* on curve *c* gives the period of reversal from normal current in one direction to normal current in the opposite direction. This period is much shorter than the full period represented by *g f* which would be obtained without local currents. The period *d f*, however, may not differ much from the period of commutation with the brush covering the width of only one bar, when the local current is high compared with the work current. In such case the gain in the period of commutation which should be obtained by means of the wider brush may be practically offset by the effect of the local currents which also increase with the wider brush, so that over a considerable range the resultant of the two effects may be practically constant. This is one indication why, in non-interpole machines, the brush width may be varied over quite a range with relatively small noticeable difference in the commutation. This may be il-

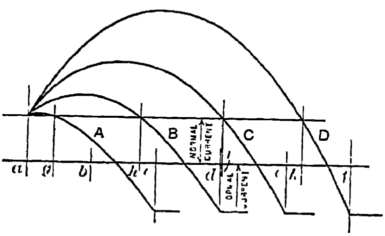


FIG. 16

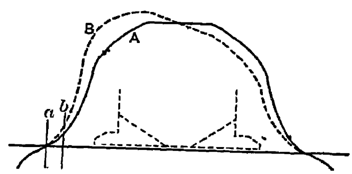


FIG. 17

lustrated by Fig. 16, in which is shown the current conditions with two to five bars spanned. In this figure *a b*, *b c*, *c d*, etc., each represent the width of one commutator bar. Therefore, curve *A*, extending over the width *a c*, represents two bars spanned. The period of reversal of the current from normal value in one direction to normal in the opposite direction is represented by *g c* for curve *A*, *h d* for curve *B*, *i e* for *C* and *k f* for *D*. A comparison of these values is interesting. Calling *a b* the period of reversal with the brush covering one bar only, then *g c* with two bars covered, is greater than *a b*. *h d* is also greater than *a b*, but less than *g c*, while *i e* is slightly less than *a b*, and *k f* is considerably less. However, the variation between *g c* and *k f* is much less than between *a c* and *a f* which would be the corresponding periods with no local currents.

It should be borne in mind that the above curves are only relative, depending upon the comparative values of the local and work currents and assuming a constant brush resistance

which is not correct, but they serve to illustrate the general principle This method of presentation is simply a skeleton of the problem of commutation when local currents are present in the short circuited coils and it would be beyond the scope of this paper to attempt a full solution.

Effects of Field Distortion. One of the "bugaboos" of the designer of commutating machines has been the question of field distortion. It has usually been considered that when the machine is loaded the magnetic field is more or less distorted or shifted from its normal no-load position and that commutation is affected by this distorted field.

To state the case plainly, the field distortion has practically nothing to do with the problem. The distorted field magnetism is simply a resultant of the no-load main field flux combined with that due to the armature winding. Therefore, the two components of the distorted full-load field are the no-load main field, which is fixed in space and is usually practically constant, and the armature field, which is also fixed in space but varies with the load. If the brushes are set in a certain position with respect to the no-load field, then, as this component of the resultant full load field is practically fixed in space and in value, it has no variable influence on the commutating conditions. The true variable element which does affect the commutation is the armature field, or flux, and it is in this very flux which is the basis of the preceding theory of commutation. Therefore, the distorted resultant field of a loaded machine does not present any new condition in the problem of commutation. One exception, however, can be made to the above, namely, where there is any considerable saturation in the armature teeth or in the main field pole corners. The effect of the armature magnetomotive force is to strengthen one corner or edge of the field pole and to weaken the other edge, but when saturation is pronounced the strengthening action is much less than the weakening action. The resultant of these actions is a decrease in the total value of the main field flux. If, now, this main field flux be brought back to its normal total value, or higher, a very considerable addition to the main field magnetomotive force will be necessary, which will be effective in increasing the field flux at the weaker pole corner to a much greater extent than at the highly saturated pole corner. In consequence, with load, the main field distribution, or field form, may be considered as being changed from its no-load form A, to the form B, as indicated in Fig. 17. It is, in reality, strengthened at a point b, for

example. In such case the main field will have a variable influence on the commutation, if the brush is set with a lead, as at *b*, and, to a slight extent, the effect of an interpole is thus obtained.

Effect of Brush Lead. Before taking up the problem of interpoles on direct current machines it might be well to consider the effect of brush lead, as this gives a result intermediate between true interpole and non-interpole commutating conditions.

The preceding formulas apply to non-commutating pole machines without brush lead. However, except in case of reversing machines, such as street railway motors, or hoist motors, etc., it is usual practice to give a forward lead to the brushes of direct current generators or a slight backward lead to direct current motors. The effect of giving a lead at the brushes of a non-interpole direct current machine may be considered as being equivalent to the effect of an interpole with the exception

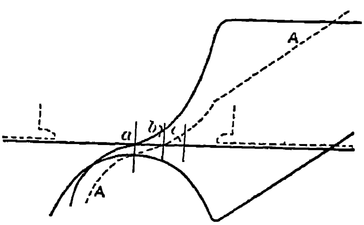


FIG. 18

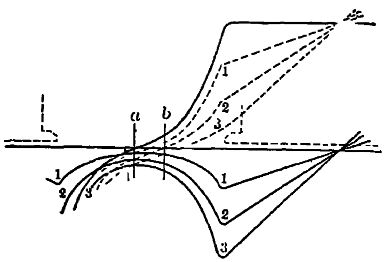


FIG. 19

that correct flux conditions and proper commutation, with any given brush setting, are obtained only for one given load.

As described before, with a non-interpole machine the armature winding sets up a flux in the interpolar space. With no-lead at the brushes this flux is usually a minimum midway between the poles and rises toward the polar edges. The flux from the adjacent main poles has a zero value midway between the poles and rises toward the polar edges, but has opposite polarities at the two sides of the midpoint. This is illustrated in Fig. 18. The resultant of the armature and field fluxes is indicated by the dotted line *A*. This resultant falls to zero at one side of the midpoint and then rises in the direction opposite to that of the flux due to the armature ampere turns. At the other side of the midpoint the two fluxes add, giving an increased resultant flux in the same direction as the interpolar flux due to the armature. From this figure it is evident that if the point of

commutation is shifted from a to the point of zero interpolar flux b, then commutation will occur without any interpolar flux to be taken into account, that is, the e.m.f. generated by the short circuited armature conductors may be due to the slot and end winding fluxes only. If the brushes are shifted still further in the same direction to c, then, not only will the interpolar armature flux be annulled but a flux in the opposite direction would be cut by the short circuited armature conductor, which will generate an e.m.f. in opposition to that due to the armature fluxes in the slots and end windings. Consequently, the commutation can be materially assisted by such lead at the brushes.

The difficulty in the use of this method of commutation lies in the fact that the commutating or reversing flux at c is the resultant of the main field flux and the armature interpolar flux at this point, and the latter flux varies with the load, while the former remains practically constant. Therefore the zero point of the resultant field shifts backwards or forwards with change in load and the density of the commutating field beyond the zero point will therefore change with the armature current. In consequence, if the brushes are shifted into a suitable resultant field c at a given current, then with a different load the intensity of this field at c will be changed, and unfortunately the change will be *in the opposite direction* from that desired. In other words, the density of this resultant field will decrease with increase in load, whereas just the opposite effect is desired for good commutation over a wide range in load.

In practice, however, an average condition is found which, in many cases, will give reasonably good commutation over a relatively wide range in load. The brushes may be shifted at no-load into an active field in such a way as to generate an e.m.f. in the armature coils of a comparatively high value. This e.m.f. will circulate considerable local current through the brush contacts and the amount of lead which can be given is dependent, to a certain extent, upon the amount of local current which can thus be handled without undue sparking

As the load is increased the strength of the resultant field, corresponding to this brush position, will be decreased, and with some value of the current this field will be reversed in direction. At this point the e.m.f due to this field is added to the e.m.f. due to the slot and end winding fluxes. Obviously the limiting condition of commutation will be reached at a much higher current than would be the case if no load at all had been given. This condition is represented in Fig. 19, in which curves 1, 1, 2, 2, 3, 3,

etc., represent the armature and resultant flux distributions with various loads. In this figure the brushes are given a lead so that commutation occurs at a point corresponding to *b*.

It is obvious that at heavy load a still greater lead at the brushes might give improved commutating conditions. However, if the load were suddenly removed without moving the brushes toward *a*, then the short circuited coils would be cutting the main field at such density that serious sparking or flashing might occur.

One serious objection to this method of commutation is that the distribution of the resultant field is practically such that equally good commutation cannot be obtained for all the coils in one slot when there are several coils or commutator bars per slot. All the coils of one slot must pass under a given position or value of the interpolar magnetic field at the same instant, while the commutator bars to which these coils are connected must pass under the brush consecutively. If the field intensity is just right for good commutation as the first coil per slot passes under the brush, then it may be entirely too great by the time the last coil is commutated. For good commutation with a number of coils in one slot, the resultant interpolar flux should have practically constant value over the whole range represented by the period of commutation of all the coils in one slot. This condition, however, is extremely difficult, or is frequently impracticable, to obtain with the ordinary non-interpole machine.

The above treatment of the problem of the effect of the brush lead has been based upon the armature interpolar magnetic field being located in the same position with lead as when there is no lead at the brushes. It has been assumed heretofore that the non-interpolar flux due to the armature winding has a minimum value midway between the main poles and rises uniformly toward two adjacent pole corners. This, however, is only true when the point of commutation, or brush setting, is midway between the poles. When the brushes are shifted toward either pole the point of maximum armature magnetic potential is shifted in the same way. This means that the distribution of the armature interpolar flux will be modified directly by the position of the brushes. Instead of rising uniformly toward the two pole corners, with a minimum value midway between, it will have a minimum at one side of the midpoint, this being at the opposite side from the point of brush contact, and will have

an increased value on the side toward which the brushes are shifted. This is illustrated in Fig. 20 in which A represents the armature interpolar flux distribution with the brush at a, while B represents it with the brush at b.

This increased armature interpolar flux due to the brush shifting means that the resultant interpolar flux due to both the armature and main field fluxes will cross the zero line at a point further removed from the midpoint than in the case of no lead at the brushes. Consequently, in order to obtain a given useful commutating field the brushes must be given a greater amount of lead and this in turn shifts the zero point still further Thus, the act itself of shifting the brushes makes the commutating conditions more difficult.

The calculation of the commutating conditions with any given lead therefore resolves itself into a determination of the resultant fluxes in which the coil is short circuited or commutated and the e.m fs generated by such fluxes. For the slot and end winding fluxes the calculation will be the same as for no-lead at the brushes The resultant flux in the interpolar space is the only condition which will introduce any variation from the preceding formulæ and methods of calculation This part of the problem resolves itself simply into the determination of the resultant interpolar flux at the point of commutation for any given load The corresponding e.m.f can then be calculated. This, combined with the e.m.fs. due to the slot and end windings, gives the total short-circuit e.m.f The method is, in principle, exactly the same as given before, except that the determination of the interpolar flux will be modified.

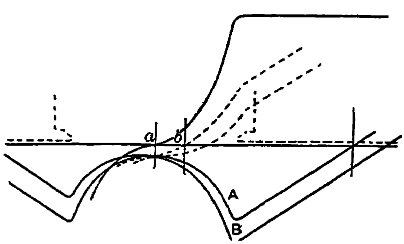


FIG 20

Summation of Formulæ In order to obtain the total voltage in the short circuited coil a summation should be made of the four separate voltages which have been derived for the interpolar,

end, slot and band fluxes. In reality it is the resultant fluxes which should be combined, but as the voltages to be derived from these fluxes represent somewhat different terms, a better procedure appears to be the summation of the voltages. Also, in practice it is the e.m.fs. generated by the different fluxes, rather than the fluxes themselves, which are desired.

The e.m.f. derived from the interpolar flux is

$$E_c = c_1 \times \frac{I_c\ W_t\ T_c R_s}{10^8} \quad \frac{2\,p\,\pi\,D\,L}{(0.25\,p+0.5)\ (\pi\,D-P\,p)}$$

where c_1 is a correcting factor for chord winding, etc.

The formula for the end flux voltage is,

$$E_c = c_2 \times \frac{I_c\ W_t\ T_c R_s}{10^8} \times \frac{4.3\ (2\,h+m)}{\sin\ \theta} \times \log 2\,N$$

where c_2 represents the correcting factor for chord windings, etc.

The formula for the slot flux voltage is,

$$E_c = c_3 \times \frac{3.19\,I_c\ W_t\ T_c\ R_s\ L}{10^8} \quad \frac{(2.666\,d+4\,a+t+2.16\,s\ \sqrt{n})}{s}$$

where c_3 is the correcting factor for the brush width, chord winding, etc., and,

For the bands,

$$E_c = c_4\,\frac{2\ \phi_b\ N\ p\ T_c\ R_s}{10^8}$$

where c_4 is the correcting factor for chord winding, brush width, etc.

Therefore,

$$E_c\ \text{total} = \frac{I_c\ W_t\ T_c\ R_s}{10^8}\left[c_1\ \frac{2\,p\,\pi\,D\,L}{(\,(0.25\,p+0.5)\ (\pi\,D-P\,p)\,)} + \right.$$

$$c_2\ \frac{4.3\ (2\,h+m)}{\sin\,\theta}\ \log 2\,N +$$

$$\left. c_3\left(3.19\,L\frac{(2.666\,d+4\,a+t+2.16\,s\ \sqrt{n})}{s}\right)\right]$$

$$+c_4 \times \frac{2\ \phi\ N\ p\ T_c\ R_s}{10^8}$$

It is evident from this last equation that when there are no bands over the core the total e.m.f. in the short circuited coil is directly proportional to the current per armature coil or conductor. If the bands saturate, as would usually be the case with any considerable load, then the e.m.f. is no longer directly proportional to the current. Attention is called to this point as it has some bearing in the design of interpole machines.

Condensed Approximate Formula. The above formula can be simplified very considerably by certain approximations which introduce but little error within the range of ordinary design.

First, the expression, $\frac{p}{(0.25\,p+0.5)\,(\pi\,D-P\,p)}$ does not seem to be capable of any general simplification. In fact, as shown from its derivation, it is not a general term, but applies only to certain constructions and may appear in a quite different form for other constructions. Therefore this expression must be used with judgment in any case. Moreover, this term appears only in non-interpole machines or in interpole machines only when the interpoles are narrower than the armature core or the number of interpoles is less than that of the main poles. Therefore this term may be neglected in many cases where interpoles are used.

Second, the expression $4.3\,\frac{(2\,h+m)}{(\sin\,\theta)}\,\log\,2\,N$ can be changed as follows:

$4.3\,\frac{(2\,h+m)}{(\sin\,\theta)}=\frac{4\,\pi\,D}{p}$, with reasonable accuracy within the ordinary limit of design,

And $\log\,2\,N=0.9+0.035\,N$, with an error of about 4 per cent within the range of 6 to 24 slots.

Therefore $4.3\,\frac{(2\,h+m)}{(\sin\,\theta)}\,\log\,2\,N=\frac{4\,\pi\,D}{p}\,(0.9+0.035\,N)$, approximately.

This is simpler to handle, in practice, than the original term.

Third, the expression, $\frac{2.666\,d+4\,a+t+2.16\,s\,\sqrt{n}}{s}$ can be simplified very materially.

Let the total depth of slot be represented by d_s, which is equal to $2\,d+a+1.5\,t$, approximately.

Then, the term, $2.666\,d+4\,a+t$ can be changed to $\frac{4d_s}{3}+\frac{8\,a-3\,t}{3}$

Assuming $a=0.25$ and $t=0.15$, then

$$\frac{8\,a-3\,t}{3}=0.52 \text{ approximately.}$$

$$\text{Therefore, } \frac{2.66\,d+4\,a+t}{s}=\frac{4d_s}{3\,s}+\frac{0\ 52}{s}$$

This is a very close approximation within the ordinary working range of slot dimensions. Therefore, the above expression becomes, $\frac{4d_s}{3\,s}+\frac{0.52}{s}+2.16\,\sqrt{n}$, which is much simpler to use in practice.

Fourth, in the simplified equation π appears in the first and second terms, and 3.19 appears in the third term. These are so nearly equal that π may be used as a common factor for the three terms.

The combined formulæ for the total voltage per armature coil thus becomes, in approximate form,

$$E_s=\frac{I\ W_t\,T_c\,R_s\,\pi}{10^8}\left[c_1\,\frac{2\,p\,D\,L}{(0.25p+0.5)(\pi D-Pp)}\right.$$

$$+c_2\,\frac{4\,D}{p}\,(0.9+0.035\,N)+$$

$$\left.c_3\,L\,\frac{(1.33\,d_s+0.52+2.16\,s\,\sqrt{n})^*}{s}\right]+c_4\,\frac{2\,\phi_b\ Np\,T_c\,R_s}{10^8}$$

This appears to be about as simple a form as the equation can be put into when all the factors are to be included. It will be shortened for machines without magnetic bands on the core and in many interpole machines the term derived from the interpolar flux may be omitted. For a given line of machines which are all of similar design, etc., it is probable that the terms can be further combined and simplified.

INTERPOLAR MACHINES

In the interpole machine a small pole is placed between two adjacent main poles for the purpose of setting up a local magnetic flux under which the armature coil is commutated. This local

*For ordinary working range of slot dimensions, $2\,16\,s\sqrt{n}=1.07\times$ tooth pitch at armature surface. This formula may be further simplified by substituting $1{,}07\,Pt$ for $2.16\,s\sqrt{n}$, Pt being the tooth pitch at the armature surface.

flux, in order to assist commutation, must be opposite in direction to the interpolar flux set up by the armature winding itself. To set up this flux in the opposite direction the magnetomotive force of the interpole winding obviously must be greater than that of the armature winding in the commutating zone.

An armature coil, cutting across this interpole flux, generates an e.m.f. proportional to the flux, the speed and the number of conductors in series. This e.m.f. is in opposition to the e.m.f. in the short circuited coils, generated by the slot and end winding fluxes. For ideal commutation these e.m.fs. are not only in opposition, but they should also be of practically equal value. For perfect commutation the current in a short circuited coil should die down to zero value at about a uniform rate and should then rise to normal value in the opposite direction by the time the coil passes out from under the brush, as was illustrated in Fig. 12. This is the condition when no local currents are developed in the short circuited coils and this can only be obtained when the interpole e.m.f. at all times, balances the armature e.m.fs. in the short circuited coils.

Looking at the problem broadly, the resultant magnetic fluxes and e.m.fs. may be assumed as made up of two components which can be considered singly. One of these components is that which would be obtained *with the armature magnetomotive force alone acting through the various flux paths, including the interpole.* The other would be that which would be obtained with the *full interpole magnetomotive force alone,* the armature magnetomotive force being absent. Saturation is not considered in either case.

Considering the first component, due to the armature magnetomotive force alone, there would be the slot and the end fluxes with their short circuit e.m.fs., as already described, and in addition, there would be a relatively high flux, and short-circuit e.m.f. due to the good magnetic path furnished by the interpole core. In case the interpole does not cover the full width of the armature, or the number of interpoles is less than the main poles, there will also be some interpolar flux and e.m.f., as already described.

Considering the second component, *the entire interpole magnetomotive force* would set up a relatively high flux through the interpole magnetic circuit and a correspondingly high e.m.f. would be generated in a short circuited armature coil cutting this flux.

When these two components are superimposed, it is seen that the interpole flux due to the armature magnetomotive force is in direct opposition to that due to the interpole magnetomotive force and therefore only the e.m.f. due to their difference need be considered. As the interpole winding has the higher magnetomotive force, the resultant interpole e.m.f. is in opposite direction to the armature e.m.fs., and should be sufficient to neutralize them. This way of considering the problem avoids a number of confusing elements which would complicate the explanation, if given in detail.

In practice it is difficult to obtain exact equality between the interpole and armature e.m.fs. That due to the armature fluxes is generated in all parts of the coil including the end winding, while the e.m.f. due to the interpole flux is generated only in that part of the coil which lies in the armature slots. However, it makes no difference in what part of the coil the e.m.f. due to the interpole is generated provided it is of such value that it properly opposes and neutralizes the various e.m.fs., due to the armature fluxes. Therefore, in practice the interpoles need not have the same width as the armature core and, where space and magnetic conditions will permit, the number of interpoles can be made half that of the main poles.

According to the method outlined, the whole problem of the design of the interpole depends, first, upon the determination of the e.m.fs. due to the armature fluxes, and, second, upon the determination of such interpole flux as will generate an e.m.f. in the short circuited armature coils which will equal, or slightly exceed, the armature e.m.fs.

Interpole Calculations. Assuming that all the armature fluxes, except the interpolar, are unaffected by the presence of interpoles, the armature e.m.f. to be balanced by the interpole would be represented by the formula

$$E_c = \frac{I_c\, W_l\, R_s\, T_c\, \pi}{10^8}\Bigg[c_1\,(L-L_1)\;\frac{2\,D\,p}{(0.25\,p+0.5)\;(\pi\,D-P p)}$$

$$+c_2\left(\frac{4\,D}{p}\right)(0.9+0.035\,N)+$$

$$c_3\,L\,\frac{1.33\,d_s+0.52+2.16\,s\,\sqrt{n}}{s}\Bigg]+c_4\,\frac{2\,\phi\,N\,p\,T_c\,R_s}{10^8}$$

However, the flux above the slot, from the tooth top, is very considerably modified by the interpolar flux. In fact most of this should be omitted It may be assumed that the flux across the slot, above the upper coil, simply " bulges " up slightly into the air gap, and the remainder of the usual tooth top flux is absent, except when the interpole does not cover the full armature width. Therefore, in the above formula, the term $L\times 2\ 16\sqrt{n}$ should be changed to $(L-L_1)\times 2\ 16\sqrt{n}$ and the term $\frac{1.33\ d_s+0.52}{s}$ replaced by $\frac{1.33\ d_s+0.7}{s}$

Then, the corrected resultant of all the armature e.m.fs. becomes

$$E_c=\frac{I_c W_t R_s T_c \pi}{10^8}\left[c_1 (L-L_1)\frac{2Dp}{(0.25p+0.5)(\pi D-Pp)}\right.$$

$$+c_2\times\frac{4D}{p}\ (0.9+0.035\ N)$$

$$\left.+c_3 L\ \frac{(1.33\ d_s+0.7)}{s}+c_3 (L-L_1)\times 2.16\sqrt{n}\right]+c_4\times\frac{2\phi\ Np R_s T_c}{10^8}$$

In this formula

L represents the width of the armature core.

L_1 represents the effective width of interpole at the gap on the basis of the full number of interpoles.

$L-L_1$ is the difference between the width of the armature core and the interpole face. This term enters when the interpole is narrower than the armature core. When alternate interpoles are omitted and the remaining interpoles are of the same width as the armature core the conditions are practically the same as when the full number of interpoles are used but with their width equal to half the core width. Other combinations should be treated in the same way so that the above formula can be taken to represent the general conditions.

In practice it is desired that the resultant interpole e.m.f., and therefore the interpole flux, vary in proportion to the armature short-circuit e.m.f. which is to be neutralized. As shown by the last equation, this e.m.f. is proportional to the armature

current, except where there is saturation in the armature flux path, as in the case of magnetic bands over the core. Therefore the interpole magnetomotive force should vary in proportion to the armature current, neglecting core bands. In consequence, in practice the interpole winding is always connected in series with the armature winding.

The interpole magnetomotive force can be considered as made up of two components, one of which neutralizes the armature magnetomotive force, and the other component represents the ampere turns which set up the actual interpole flux. The first component will be referred to as the neutralizing ampere turns or neutralizing turns, and the other as the magnetizing ampere turns or magnetizing turns.

Let T represent the total interpole turns for one interpole,

T_i represent the total magnetizing interpole turns for one interpole.

T_a represent the total effective "armature turns per pole" $= \dfrac{\text{total eff. ampere turns of armature}}{\text{number poles} \times \text{total current}}$, and

I represent the amperes per interpole coil.

Then $I\,T_i = I\,T - I\,T_a$, or, $T = T_a + T_i$.

Let g = effective air gap per interpole.

B_i = flux density under the interpole, and

E_i = e.m.f. in an armature coil of turns T_c due to the interpole flux

Then,

$$B_i = \frac{3.19\,I\,T_i}{g}$$

The e.m.f. due to one interpole is equal to

$$\frac{B_i\,\pi\,D\,L_1\,T_c\,R_s}{10^8}$$

Or, for two interpoles

$$E_i = \frac{3.19\,I\,T_i\,\pi\,D\,L_1 \times 2\,T_c\,R_s}{g \times 10^8}\ *$$

*If average slot e. m. f. is used in calculating E_c (See Note on page 215), this expression should be multiplied by a factor C_p to obtain average value of E_i. C_p is the ratio of the average flux density in the commutating zone, to the maximum density, B_i.

This e.m.f. should be equal to the e.m.f. generated in the same coils by the armature flux, or $E_i = E_c$. Therefore,

$$\frac{3.19\, I\, T_i\, \pi\, D\, L_1 \times 2\, T_c\, R_s}{g \times 10^8} = \frac{I_c\, W_t\, T_c\, R_s\, \pi}{10^8}$$

$$\left[c_1\,(L-L_1)\,\frac{2\,D\,p}{(0.25\,p+0.5)\;(\pi\,D-Pp)}\right.$$

$$+c_2 \times \frac{4\,D}{p}\,(0.9+0.035\,N)+c_3\,L\,\frac{(1.33\,d+0.7)}{s}$$

$$\left.+c_3\,(L-L_1)2.16\,\sqrt{n}\,\right]+c_4\,\frac{2\,\phi\,Np\,R_s\,T_c}{10^8}$$

In the second term of this equation $I_c\ W_t = I \times T_a' \times 2p$, where T_a' = total armature turns per pole, as distinguished from effective turns per pole T_a, and $T_a' = \frac{T_a}{1-b\,p}$, where $b = \frac{B_t\,T_c}{W_t}$ as will be shown later under the subject of " Effective Armature Ampere Turns." Therefore, neglecting magnetic bands on the core, the above expression becomes,

$$T_i = \frac{T_a\,p\,g}{3.19\,D\,L_1\,(1-b\,p)}\left[c_1 \times \frac{(L-L_1)\,2\,D\,p}{(0.25\;p+0.5)\;(\pi\,D-Pp)}\right.$$

$$+c_2 \times \frac{4\,D}{p}\,(0.9+0.035\,N)+c_3\,L\,\frac{(1.33\;d+0.7)}{s}$$

$$\left.+c_3\,(L-L_1)\,2.16\,\sqrt{n}\right]$$

$$T = T_i + T_a = T_a\left[1+\frac{p\,g}{3.19\,D\,L_1\,(1-b\,p)}\right.$$

$$\left(c_1\,(L-L_1)\,\frac{2\,D\,p}{(0.25\;p+0.5)\;(\pi\,D-Pp)}\right.$$

$$+c_2 \times \frac{4\,D}{p}\,(0.9+0.025\,N)+c_3\,L\,\frac{(1.33\,d_s+0.7)}{s}$$

$$\left.\left.+c_3\,(L-L_1)\,2.16\,\sqrt{n}\right)\right]$$

If the full number of interpoles is used, and each covers the full width of the armature, then $L-L_1=0$, and

$$T=T_a\left[1+\frac{p\,g}{3.19\,D\,L_1\,(1-b\,p)}\left(c_2\times\frac{4\,D}{p}\,(0.9+0.035\,N)\right.\right.$$

$$\left.\left.+c_3\,L\,\frac{(1.33\,d_s+0.7)}{s}\right)\right]$$

Therefore the total interpole turns for one pole are equal to the effective armature turns per pole multiplied by a constant which is a function of the proportions of the machine. However, this holds true only for the condition of no saturated path for the armature flux, such as magnetic bands.

The above formula gives the interpole turns for two interpoles acting on each armature coil. With but one interpole per coil the number of conductors per armature coil generating the interpole e.m.f. is halved so that the flux density must be at least doubled, and the effect of the armature flux in the interpolar space over the other half of the armature coil must also be taken into account. This can be done in the preceding formula by using the equivalent value of L_1.

With half the number of interpoles the effective gap length, g, will not be the same as with the full number of interpoles with the same mechanical gap, for the flux from the interpole may be considered as returning across the gap of the two adjacent main poles and the value of g must be increased to represent the total resultant gap.

Let g_e represent the effective resultant gap,
g_m represent the effective gap under the main poles,
A_i represent the area of the interpole gap, and
A_m represent the area of one main pole gap.

These areas can be derived from the field distribution or " field form " of the main and the interpoles.

Then, the effective resultant gap $g_e=g+\frac{A_i}{2\,A_m}\,g_m$, and this should be used instead of g

With half the number of interpoles and on the basis of the interpole flux returning through the two adjacent main poles, it may be assumed that this flux weakens the total flux in one pole and strengthens that of the other pole a like amount. If

there is no saturation in the main poles or armature teeth under them, then no additional ampere turns, other than for the increased gap, will be required on account of the main poles carrying the interpolar fluxes. However, where there is much saturation of the main poles or teeth, then additional interpole ampere turns will be required, as will be described later in connection with effects of saturation.

Chord Windings with Interpoles. Chorded armature windings can be used with interpoles with satisfactory results provided the interpoles are suitably proportioned. There are apparently some advantages with such an arrangement, but there are also disadvantages of such a nature that it is questionable whether it is advisable to use chord windings with such machines, except possibly in special cases. When chorded windings are used with interpoles, the e.m.f. due to the armature flux is usually much smaller than with a pitch winding and thus fewer interpole magnetizing turns are required. Also, the effective armature turns which must be neutralized by the interpole are reduced somewhat, which also means a slight reduction in interpole turns. Against these advantages must be charged the disadvantage of a wider interpole face. This in itself would not be objectionable where there is space for such wider pole face, but if the space between the main poles must be increased it may lead to sacrifice in the proportions of the main poles or changes in the general dimensions, such that the result as a whole is less economical than with a pitch winding.

Effective Armature Ampere Turns. The term T_a representing the effective armature ampere turns should be considered, as the value of this term is influenced by a number of conditions, such as the number of bars covered by the brush, the amount of chording in the armature winding, etc. With a full pitch winding and neglecting the reduction in current in the short circuited coils, the magnetomotive force of the total armature winding is represented by the expression, $\frac{I_c\,W_t}{2}$, and per pole it is, $\frac{I_c\,W_t}{2\,p}$. However, when the brush spans several coils, so that a number of armature coils are short circuited at the same time, the average current in these short circuit coils should be considerably less than the normal value so that the effective ampere turns per pole is correspondingly reduced. Allowance must be

made for this reduction as it has considerable influence in determining the correct number of interpole turns.

On the basis of no local currents, the average value of the current in the short circuited coils is just half that of the work currents per conductor.

Let B represent the total number of commutator bars,
B_1 represent the number of bars spanned by the brush,
p_1 represent number of current paths, and
p number of poles.

Then, $\frac{B\,T_c}{p_1\,p}$ = total number of armature turns per pole, and

$\frac{B_1\,T_c}{2\,p_1}$ = number of turns by which the total armature turns per pole must be reduced to obtain the effective turns per pole, or,

$$T_a = \frac{B\,T_c}{p\,p_1} - \frac{B_1\,T_c}{2\,p_1}$$

$$B\,T_c = \frac{W_t}{2}, \quad \therefore T_a = \frac{W_t}{2\,p\,p_1} - \frac{B_1\,T_c}{2\,p_1}$$

Let $B_1\,T_c$ be represented as a percentage of W_t, or $B_1\,T_c = b\,W_t$

Then, $T_a = \frac{W_t}{2\,p_1\,p}\,(1 - b\,p)$

$$I\,T_a' = \frac{I_c\,W_t}{2\,p} = \frac{(I_c\,p_1)\,W_t}{2\,p\,p_1} = \frac{I\,W_t}{2\,p\,p_1}, \quad \therefore T_a' = \frac{W_t}{2\,p\,p_1}$$

Therefore, $T_a' = \frac{T_a}{(1 - b\,p)}$.

Chorded windings also have an influence on the effective armature ampere turns per pole. When the winding is chorded one slot, for example, then, in one slot per pole, the upper and lower coils will be carrying current in opposite directions and their magnetizing effects will be neutralized. In consequence, the total effective armature ampere turns are correspondingly reduced and this must be allowed for in determining the interpole turns.

Conditions Affecting Interpole Proportions. The foregoing formulæ have been based upon the use of interpoles of such proportions that the interpole flux varies directly as the magnetizing current and its distribution over the commutating zone is such as will give the proper opposing e.m.f. at all times.

However, the proportionality of flux to current can only be true as long as there is no saturation in the interpole magnetic circuit. Such saturation is liable to be found in practice and not infrequently it is quite a problem of design to avoid it within the working range of the machine.

Also, another difficult problem lies in so designing the interpole face that the flux distribution in the commutating zone is such that its e.m.f. will properly balance the armature e.m.fs. in the short circuited coils, especially as the latter are generated by cutting fluxes which may be distributed in a quite different manner from the interpole flux.

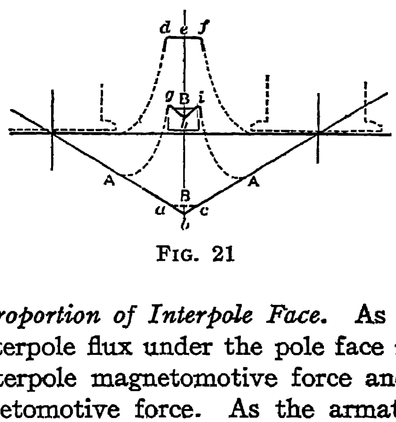


FIG. 21

Shape and Proportion of Interpole Face. As already shown, the effective interpole flux under the pole face is the resultant of the total interpole magnetomotive force and the opposing armature magnetomotive force. As the armature winding is distributed over a surface and the interpole winding is of the polar or concentrated type, the resultant magnetomotive force would normally be such as would not tend to give a uniform flux distribution under the interpole unless the interpole face is properly shaped or proportioned for such distribution. The conditions may be illustrated in Fig. 21. In this figure the lines *A A* represent the armature magnetomotive force, with a full pitch winding, and the brush covering one commutator bar. The heavier part of the lines *a b c* at the peak of the magnetomotive force diagram, represents the armature magnetomotive force which would be obtained under the interpole face, and also the flux distribution which would be obtained, with no interpole

magnetomotive force, and with uniform gap under the pole faces. In opposition is shown the interpole magnetomotive force and flux distributions *d e f* for corresponding conditions. The resultant magnetomotive force is represented by *g h i*, and with a uniform gap under the pole, the resultant interpole flux would have a similar distribution. Instead of this, either a flat or, in some cases, the reverse distribution is required, that is, with a slight "hump" in the middle instead of a depression. By properly shaping the pole face so as to give an increased air gap toward the edges, the flux distribution can be made practically anything desired. In some cases a relatively narrow pole tip with a very large air gap will give a close approximation to the desired flux distribution.

However, in practice the above distribution of the armature magnetomotive force is rarely found. The use of brushes which cover more than one commutator bar serves to cut off or flatten out the pointed top of the armature magnetomotive force diagram, as shown by the dotted line *B*, in Fig. 21, and thus lessen the depression at the center of the resultant magnetomotive force distribution.

As intimated before, this problem of proportioning the interpole face turns upon the determination of the armature e.m.fs. in the short circuited coils which have to be balanced by the interpole. If the different armature e.m.fs. are determined for the whole period of commutation and then superimposed, the resultant e.m.f. indicates the flux distribution required under the interpole. Usually the e.m.fs. due to the end winding, and to the interpolar flux, if any, will be practically constant during the whole period of commutation. If no local currents are present the e.m.f. due to the slot flux will also be practically constant, although it may be slightly reduced near the beginning and end of the commutation period. The sum of these e.m.fs. should therefore be practically constant over the whole commutation period and therefore, in a well designed machine, the interpole flux density should be practically constant over the whole commutation zone. As explained before, special shaping of the poles and pole face will be necessary, in most cases, to obtain exactly this proper flux distribution. Large interpole air gaps are obviously advantageous in obtaining such distribution. In fact, a very small interpole gap makes the determination of the proper interpole face dimensions very difficult in many cases. On account of the interpole usually covering less than two

armature teeth, the ordinarily accepted methods of determining the effective length of air gap under a pole will not apply, in many cases, which may lead to a slight error in the results. Practically the effective gap under the narrow interpole will usually be longer than determined by the ordinary methods. This partly explains the fact that, in some cases, an increase in mechanical clearance between the interpole face and the armature core does not require anything like a corresponding increase in the interpole magnetizing ampere turns. The effective interpole air gap increases, but at a much less rate than the mechanical gap.

The brush setting in relation to the interpole is of great importance. The point of maximum armature magnetomotive force is definitely fixed by the brush setting. With the interpole fixed in position, any shifting of the brushes backward or forward will obviously change the shape of the resultant magnetomotive force distribution under the interpole face and in consequence the flux distribution will be changed. With but one armature coil per slot and the brush covering but one commutator bar, good commutating conditions might be found over a considerable range of brush adjustment, by suitably varying the interpole ampere turns. However, with two or more coils per slot and with the brush short circuiting several bars, any marked change in the resultant interpole magnetomotive force and flux distribution will mean improper commutation for some of the coils. Proper brush setting is therefore of first importance.

It has been assumed in the foregoing treatment, that an exact balance between the interpole and armature e.m.fs. will give the best conditions. From certain standpoints, this is true, but in practice usually a slight excess in the interpole strength, or "over-compensation" of the interpole, as it is frequently called, is advantageous. Reference to Fig. 14 shows that in a machine without interpoles, and therefore without compensation, the current flowing between the brush contact and the commutator is crowded toward one brush edge, this being the edge at which the commutation of a coil is completed, that is, at the so-called forward brush edge. With over-compensation the opposite effect occurs—that is, the brush current density is below the average at the forward edge. This is, to a certain extent, a desirable condition. Also, if there is any saturation of the interpole circuit at overloads, the over excitation of the interpole winding can take care of the saturation ampere turns, so that

normal compensation can be obtained at considerably higher load than in a machine with no over compensation. Furthermore, over compensation is desirable on account of the effect of the resistance of the coils undergoing commutation, which heretofore has been neglected as being of minor importance. Such resistance tends to lower the current density at the middle of the brush contact, and increase it toward the brush edges. Over compensation will oppose this at the forward edge, but increase it at the back edge, which is less objectionable. Also, as shown in Fig. 21, there is liable to be a depression at the center of the interpole flux distribution, if the pole face is not properly shaped. This depression tends to cause higher current densities at the brush edges. Over compensation again tends to reduce this density at the forward brush edge. Thus there are several good reasons for slight over compensation, and practical operation bears this out, especially on high voltage machines, where the short circuit e.m.fs. average higher than in other machines.

Balanced Circuits. It has been assumed that the armature ampere turns per pole have been the same for all poles. This will be true for the usual two-circuit or series type of winding, or its allied combinations, but is not necessarily true of the parallel type of armature winding. In such a winding a number of circuits are connected in parallel at the brushes, and, unless ample provision be made for equalizing the different circuits, they may not carry equal currents at all times. As the resultant interpole flux and e.m.f. is directly dependent upon the opposing armature ampere turns, it is obvious that any inequalities in the armature currents would lead at once to incorrect interpole conditions. A poorly equalized parallel-wound armature might furnish conditions such that the interpoles cannot be adjusted for satisfactory operation. Also paralleling of the interpole windings, unless care be taken to insure equal current division among the circuits, is liable to lead to trouble.

Saturation of the Interpole Circuit. Heretofore the interpole turns T, as determined, have been only those required for forcing the resultant interpole flux across the effective interpole air gap, and nothing has been allowed for any turns required for magnetizing the parts of the interpole circuit other than the gap. Where such additional turns are required they must be added to the turns T, already determined.

Saturation in the interpole magnetic path is the principle cause for such additional turns, but saturation in the various

flux paths may occur in such a way as to be either harmful or beneficial, depending upon where it is located. Beneficial saturation may be assumed to be such as will reduce the armature short circuit e.m.fs., while harmful saturation tends to reduce the interpole e.m.f.

While the useful interpole flux passing into the armature may be relatively low—say one-fifth that required for saturation of the interpole material—the leakage flux between the interpole and the two adjacent main poles is often very much greater than the useful flux so that the interpole at the part where it carries the highest total flux may be worked up to possibly half saturation, or higher, with normal load on the machine. The interpole leakage flux is due to the *total ampere turns on the interpole*, while the useful interpole flux is due only to the magnetizing component of the interpole ampere turns, which may be as low as 15 per cent to 25 per cent of the total interpole ampere turns. The leakage flux is thus liable to be a high percentage of the total interpole flux.

While the ampere turns on the interpole will rise in direct proportion to the current, the effective magnetizing component will rise in direct proportion only below saturation of the interpole circuit. Any ampere turns required for saturating this circuit will be taken from the magnetizing component of the interpole winding. Therefore, when any appreciable saturation occurs, the effective magnetizing component will not vary in proportion to the current, and the interpole e.m.f. will not vary in proportion to the armature e.m.fs. As the magnetizing component of the interpole winding usually represents a relatively small number of ampere turns per pole a comparatively slight saturation in the interpole circuit may have an appreciable effect. It is therefore advisable to work at as low a saturation as possible in the interpole circuit so that practically no saturation occurs within the ordinary working range of the machine.

Where saturation occurs in any of the armature flux paths, as, for instance, with saturated bands over the armature core, the result of such saturation will serve to neutralize the effect of saturation in the interpole magnetic circuit. In other words, the armature e.m.f. will not rise in proportion to the current and therefore the opposing interpole e.m.f. does not need to increase in proportion either.

The principal source of saturation in the interpole circuit lies in the magnetic leakage from the interpole to the adjacent main

poles. Serious trouble has often been encountered by not making due allowance for such leakage. However, there may be other causes for saturation. When the full number of interpoles is used the interpole magnetic path or circuit is independent of the main pole magnetic circuit, except in the yoke and in the armature core below the slots, as indicated in Fig. 22. In the yoke it may be seen that the interpole flux is in the same direction as the main flux at one side of the main pole and is in opposition to the main flux at the other side. The same is true in the armature core. Therefore the interpolar flux tends to reduce the flux in one part of the yoke and tends to increase it in the other part. If the saturation in these parts is relatively low, then the magnetomotive force required for forcing the low and the high fluxes through the yoke will be but little greater than if these fluxes were equal. However, if the yoke is highly saturated the increase in ampere turns required for the high part much more than offset the decrease in ampere turns for the low part, so that, as a result, additional ampere turns are required for sending the interpole flux through this path. The interpole ampere turns therefore must be increased on this account, when the saturation is high. The same condition holds for the armature core.

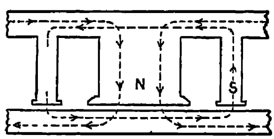


FIG. 22

A similar condition occurs where half the number of interpoles is used and when there is much saturation of the main pole and the armature teeth under it, as already referred to. This condition requires additional interpole ampere turns.

In practice, with the ordinary compact designs of direct current machines, it is usually difficult to keep the total interpole flux as low as one-third that which gives any material saturation and, not infrequently, it is much higher than this. Therefore, by direct proportion it might be assumed that such machines could carry only double to treble load without sparking badly. However, the resistance of the brushes, etc., will be of such assistance that relatively higher loads may be commutated reasonably well. For instance, with the interpole worked at about half saturation at normal load, the machine may be able to commutate considerably more than double load without undue sparking. It is also of material assistance, where heavy overloads are to be carried, to over-excite the interpole winding, that is, to make the magnetizing component somewhat greater

than required at normal load, as described before. In this case, at light loads, the interpole e.m.f. exceeds the armature e.m.f. a certain amount which is taken care of by the brush resistance as local currents will be less harmful when the work current is low. As partial saturation is obtained at overload, the two e.m.fs. become equal but at a higher load than would be the case without over-excitation of the interpole.

Commutating Conditions on Short Circuit. When a direct current generator is short circuited across its terminals, either through a low external resistance or without such resistance, a current rush will occur which will rise to a value represented approximately by the generated e.m.f. divided by the resistance in circuit. This current rush is only of short duration as the excessive armature current will react to demagnetize or " kill " the field. If the short circuit is without external resistance the current rush may reach an enormous value as the internal resistance on large machines is usually very low. This means that currents from 25 to 40 times full load may be obtained on " dead " short circuit. Experience shows that under such current rushes, any kind of direct current machine will tend to flash viciously at the brushes.

By the preceding theory and analysis a rough approximation to the commutating conditions on short circuit can readily be obtained. Assuming an interpole machine, the following conditions will be found:

1. The interpole will be highly saturated so that it is of little or no direct benefit.

2. The slot flux will rise to such a value that the armature teeth in the commutating zone are practically saturated.

3. There may be some interpolar flux from the armature, as the high interpole saturation may allow this.

4. The armature end flux, with the exception of that part due to magnetic bands, will rise practically in proportion to the current.

The following short circuit e.m.f. conditions will be obtained:

1. There will be possibly a slight e.m.f. due to the armature interpolar flux.

2. There will be an e.m.f. due to the tooth flux which is almost as high, per conductor, as could be obtained by a conductor cutting the flux *under the main field at no load*, for saturation of the armature teeth may be assumed to be the limit in both cases.

3. There will be an e.m.f. due to the end flux which may be 10 to 20 times larger than at normal full load.

Therefore, the total e.m.f. in the short circuited coil due to cutting the armature flux on dead short circuit may be higher than would be obtained *if the brushes were shifted at no load until the commutated coil lies under the strongest part of the main field.* As very few machines of large capacity would stand this latter condition without flashing, it may be assumed that they would be no more able to stand a dead short circuit without flashing. In fact, 8 to 10 times full load current will make an interpolar machine of normally good design flash badly, as it is impracticable to make an interpole of the usual type which will not saturate highly at 8 to 10 times normal current.

If, however, the interpole is combined with compensating windings in the main poles, the interpole leakage may be made so small that comparatively low saturation is obtained normally in the interpole circuit. In such case the interpole may be effective with heavier currents and the flashing load may be very much higher than with the usual type of interpole machines.

Conclusion

The foregoing is a general presentation of the problem of commutation, which is admittedly crude and incomplete in some points. In particular may be mentioned the part describing the action of local currents. Also, the method of considering the resultant action in interpole machines as the superposition of two components does not tell the whole story, but the actual analysis, in detail, of a number of these phenomena would be so confusing and complicated that a general physical conception of what takes place during commutation would be lost. In the ultimate analysis it will be found that a number of the methods described are, in reality, simply illustrations of the conditions of commutation rather than an analysis of the conditions themselves. However, the method as given throws light on many things which take place during commutation. It also includes a number of conditions which are not covered in the usual methods of dealing with this problem. For example, the number of commutator bars spanned by the brush is an important element in this method of handling the problem, whereas, in many former methods, this point was either omitted, or treated in an empirical manner. In this method the results obtained would be very greatly in error if the brush span were not included.

Any theory or method of calculation is open to question until ti has stood the proof of actual test. In consequence, the above

method has been tried on a very large number of direct current machines, including high speed direct current generators, direct current turbo-generators, direct current railway motors of all sizes, moderate- and low-speed generators of all capacities, industrial motors of various designs including adjustable speed motors and machines with half the number of interpoles. In those cases where the actual test data of the machines was very accurately obtained, the agreement between the tests and the calculated results by the above method was found to be close. In fact, the method in some cases indicated errors or inaccuracies in the test results. In a number of cases of early interpole machines there was considerable disagreement between the results of the calculation and the actual test, but, in many of these cases, later experience showed definitely that the proper interpole field strength or proportions had not been obtained in the actual test or that the proper brush setting had not been used. These cases were thus, to a certain extent, a verification of the method, for in general the greatest discrepancies between the calculated and the test results corresponded to the machines which eventually proved to have the poorest proportions or adjustment.

This theory of commutation looks complicated and cumbersome in its practical application, but it should be understood that it is, in reality, an exposition of a general method from which special and simpler methods may be derived for different types and designs of machines. It indicates plainly that the problem is so complicated that no simple formulæ or methods of calculation can be devised which will cover more than individual cases, and that such formulæ, if applied generally, will lead to error sooner or later. If, however, the general derivation of such simplified formulæ is well understood, then they may be used with proper judgment and with much less danger of error in the results. It is evident, from the general analysis, that the whole problem must be handled with judgment, for new or different conditions are encountered in almost every type of machine.

A great many problems, closely allied to that of commutation in interpole machines, have not been considered, because some of them represent special cases of the general theory, while others are somewhat outside the subject of this paper. Of the former class may be mentioned, commutation of synchronous converters, machines with distributed or true compensating

windings, the so-called "split-pole" converter, and the commutator type alternating current motors, etc. In the latter class may be included such problems as the effect on commutation of closed circuits around the interpoles, losses due to commutation, current distribution at the brush contact, etc. Some of these subjects were included in this paper as originally prepared, but on account of its undue length they had to be omitted.

PHYSICAL LIMITATIONS IN DIRECT-CURRENT COMMUTATING MACHINERY

FOREWORD—This paper was presented before the American Institute of Electrical Engineers in San Francisco, September 16, 1915, at the Electrical Congress at the Panama-Pacific International Exposition. It gives the results of the author's work on determination of commutating limits covering the period of many years of work. As regards commutation, it is, in reality, a supplement to the paper, "Theory of Commutation and Its Application to Commutating Pole Machines." On the subject of flashing, it covers some very interesting limitations, based upon experience and special tests.

This paper is, in reality, more or less of a general summary of the author's experience in direct-current machinery. Although usually looked upon as an "alternating-current man," he has probably spent as much total time on direct-current work as on alternating. Many of the limiting conditions in direct-current machinery, as described in this paper, were determined by the author himself. Many of the early more or less radical developments and improvements in direct-current machinery resulted directly from his work. A description of some of these is covered in his historical papers, entitled, "The Development of the Direct-Current Generator in America," and "The Development of the Street Railway Motor in America" which appear in the latter part of this volume.—(Ed.)

IN DIRECT-current commutating machinery there are many limitations in practical design which cannot be exceeded without undue risk in operating characteristics.

Some of these limitations are actually physical ones, and, therefore, cannot be avoided or over-stepped without very considerable departures from our present methods of construction and operation; others are not wholly physical, but are fixed largely by practical experience, and are, in consequence, subject to modification, as our experience is increased. Some of them are quite definite in nature, while others are indefinite. Some are measurable, in a quantitative sense, while others may be considered as qualitative. Noise, for instance, is a distinct limitation, in many cases, but it is difficult to fix any definite value where it is prohibitive.

Many of these limits are not sharply defined in practise, due, in many cases, to the impossibility of taking advantage of all the helpful conditions and of avoiding the objectionable ones. There are many minor conditions which affect the permissible limits of operation, which are practically beyond the scope of reliable calculation. Usually, such conditions are recognized, and allowance is made for them. It is the purpose of this paper to treat of some of the major, as well as minor, conditions which must be taken into account in advanced direct-current design. These are so numerous, and are so interwoven, that it is difficult to present them in any consecutive order.

Probably the most serious limitation encountered in direct-current electric machinery is that of commutation. This is an electrical problem primarily, but in carrying any design of direct-current machine to the utmost, certain limitations are found which are, to a certain extent, dependent upon the physical characteristics of materials, constructions, etc

A second limitation which is usually considered as primarily an electrical one, namely, flashing, (and bucking) is in reality fixed as much by physical as by purely electrical conditions.

A third limitation is found in blackening and burning of commutators, burning and honeycombing of brushes, etc. These actions are, to a certain extent, electrical, but are partly physical and mechanical, as distinguished from purely electrical.

There are many other limiting conditions dependent upon speed, voltage, output per pole, quality or kind of materials used, etc. As indicated before, these cannot all be treated separately and individually, as they are too closely related to other characteristics and limitations.

Commutation and Commutation Limits

In dealing with the limits of commutation, it is unnecessary to go into the theory of commutation, except to indicate the general idea upon which the following treatment is based. This has been given more fully elsewhere,* and therefore the following brief treatment will probably be sufficient for all that is required in this paper.

In this theory it is considered that the armature winding as a whole tends to set up a magnetic field when carrying current, and that the armature conductors cutting this magnetic field

*Theory of Commutation and Its Application to Commutating Pole Machines, Page 201.

will generate e.m.fs. just as when cutting any magnetic field. From consideration of the armature magnetomotive force alone, the flux or field set up by this winding would have a maximum value over those armature conductors which are connected to the brushes. If the magnetic conditions or paths surrounding the armature were equally good at all points, this would be true. However, with the usual interpolar spaces in direct-current machines, the magnetic paths above the commutated coils are usually of higher reluctance than elsewhere. However, whatever the magnetic conditions, the tendency of the armature magnetomotive force is to establish magnetic fluxes, and, if any field is established in the commutating zone by the armature winding, then those armature coils cutting this field will have e.m.fs. generated in them proportional to the field which is cut. As part of this armature flux is across the armature slots themselves, and part is around the end windings, both of which are practically unaffected by the magnetic path in the interpolar space above referred to, obviously, then no matter how poor the magnetic paths in the interpolar space above the core may be made, there will always be e.m.fs. generated on account of that part of the armature flux which is not affected by those paths. In the coils short circuited by the brushes, these e.m.fs. will naturally tend to set up local or short circuit currents during the interval of short circuit.

In good commutation, as the commutator bars connected to the two ends of an armature coil which is carrying current in a given direction, pass under the brush, the current in the coil itself should die down at practically a uniform rate, to zero value at a point corresponding to the middle of the brush, and it should then increase at a uniform rate to its normal value in the opposite direction by the time that the short circuit is opened as the coil passes from under the brush. This may be considered as the ideal or straight line reversal or commutation which, however, is only approximated in actual practice. This gives uniform current distribution over the brush face.

If no corrective actions are present, then the coil while under the brush tends to carry current in the same direction as before its terminals were short circuited. In addition, the short circuit current in the coil, due to cutting the armature flux, tends to add to the normal or work current before reversal occurs. The resultant current in the coil is thus not only continued in the same direction as before, but tends to have an increased value.

Thus the conditions at the moment that the coil passes out from under the short circuiting brush are much worse than if no short circuit current were generated. The reversal of the current would thus be almost instantaneous instead of being gradual as called for by the ideal commutation, and the resultant current reversed much greater than the work current alone. However, the introduction of resistance into the local circuit will greatly assist in the reversal as will be illustrated later. The ideal condition however, is obtained by the introduction of an opposing e.m.f. into the local short circuited path, thus neutralizing the tendency of the work current to continue in its former direction.

As this opposing e.m.f. must be in the reverse direction to the short circuit e.m.f. which would set up by cutting the armature magnetic field, it follows that where commutation is accomplished by means of such an e.m.f. it is necessary to provide a magnetic field opposite in direction to the armature field for setting up the commutating current. This may be obtained in various ways, such as shifting the brushes forward (or backward) until the commutated coil comes under an external field of the right direction and value, which is the usual practise in non-commutating pole machines; or a special commutating field of the right direction and value may be provided, this being the practise in commutating pole and in some types of compensated field machines. When the commutating e m f. is obtained by shifting the commutated coil under the main field, only average conditions may be obtained for different loads; whereas, with suitable commutating poles or compensating windings, sufficiently correct commutating e.m.fs. can be obtained over a very wide range of operation.

In practise, it is difficult to obtain magnetic conditions such that an ideal neutralizing e.m.f. is generated. However, the use of a relatively high resistance in the short circuited path of the commutated coil very greatly simplifies the problem. If the resistance of the coil itself were the only limit, then a relatively low magnetic field cut by the short circuited coil would generate sufficient e.m.f. to circulate an excessively large local current. Since such current might be from 10 to 50 times as great as the normal work current, depending upon the size of machine, it would necessarily add enormously to the difficulties of commutation whether it is in the same direction as the work current or is in opposition. To illustrate the effect of resistance, assume, for example, a short circuit e.m.f. in the commutated coil of two

volts, and also assume that a copper brush of negligible resistance short circuits the coil, so that the resistance of the short circuited coil itself practically limits the current to a value 20 times as large as the work current. Now replace this copper brush with one giving about 20 times as large a resistance (some form of graphite or carbon brush) then the total resistance in circuit is such that the short circuit current is cut down to a value about equal to that of the work current. This at once gives a much easier condition of commutation, even without any reversing field; while with such field, it is evident that extreme accuracy in proportioning is not necessary. Thus a relatively high resistance brush—or brush contact, rather—is of very great help in commutation; especially so in large capacity machines where the coil resistance is necessarily very low. In very small machines, the resistance of the individual armature coils has quite an influence in limiting the short circuit current.

It is in its high contact resistance that the carbon brush is such an important factor in the commutating machine. Usually, it is the resistance of the brush that is referred to as an important factor in assisting commutation. In reality, it is the resistance of the contact between the brush and commutator face which must be considered, and not that of the brush itself, which usually is of very much lower resistance, relatively. As this contact resistance or drop will be referred to very frequently in the following, and as the brush resistance itself will be considered in but a few instances, the terms "brush resistance" and "brush drop" will mean contact resistance and contact drop respectively, unless otherwise specified.

Short Circuit Volts per Commutator Bar. As stated before the armature short circuit e.m.f. per coil, or per commutator bar, is due to cutting a number of different magnetic fluxes, such as those of the end windings, those of the armature slots, and those over the armature core adjacent to the commutating zone. Each of these fluxes represent different conditions and distributions, and therefore the individual e.m.fs. generated by them may not be coincident in time phase. Therefore, the resultant e.m.f. usually may not be represented by any simple graphical or mathematical expression.

When an external flux or field is superimposed on the armature in the commutating zone, it may be considered as setting up an additional e.m.f. which may be added to, or subtracted from, the resultant short circuit e.m.f. due to the armature fluxes.

These component e.m.fs. are not really generated separately in the armature coils, for the external flux combines with part of the armature flux, so that the armature coil simply generates an e.m.f. due to the resultant flux. However, as part of the armature short circuit e.m.f is generated by fluxes which do not combine with any external flux, as in the end winding, for instance, it follows that, to a certain extent, separate e m.fs are actually generated in the armature winding in different parts of the coil. For purposes of analysis, there are advantages in considering that all the e m.fs in the short circuited armature coil are generated separately by the various fluxes. A better quantitative idea of the actions which are taking place is thus obtained, and the permissible limitations are more easily seen. In the following treatment, these component e.m.fs will be considered separately. As that component, due to cutting the various armature fluxes, will be referred to very frequently hereafter, it will be called the "apparent" armature short circuit e.m f. per coil, or in abbreviated form, "the apparent short circuit e m.f." In practise, on account of the complexity of the separate elements which make up the apparent short circuit e m.f., it is very difficult, or in many cases, impossible, to entirely neutralize or balance it at all instants by means of an e.m.f. generated by an extraneous field or flux of a definite distribution. Therefore, it should be borne in mind that, in practise, only an approximate or average balance between the two component e.m.fs. is possible. With such average balance there are liable to be all sorts of minor pulsations in e.m.f. which tend to produce local currents and which must be taken care of by means of the brush resistance. Pulsations or variations in either of the component e.m.fs. are due to various minor causes, such as the varying magnetic conditions which result from a rotating open slot armature, from cross magnetizing and other distorting effects under the commutating poles, variations in air-gap reluctance under the commutating poles, pulsations in the main field reluctance causing development of secondary e.m.fs. in the short circuited coils, etc. Some of these conditions are liable to be present in every machine; some which would otherwise tend to give favorable conditions as regards commutation, are particularly liable to set up minor pulsations in the short circuit e.m.f. Therefore, brushes of high enough resistance to take care of the short circuit e m.f. pulsations are a requisite of the present types of d-c. machines, and it may be assumed that there is but little

prospect of so improving the conditions in general that relatively high resistance brushes, or their equivalent, may be discarded. It is only on very special types of machines that low resistance brushes can be used.

With ideal or perfect commutation, the two component e.m.fs in the short circuited coil should balance each other at all times However, as stated before, this condition is never actually obtained, and the brush resistance must do the rest. With ideal commutation, the current distribution over the brush contact face should be practically uniform, and a series of voltage readings between the brush tip and commutator face should show uniform drops over the whole brush face In most cases in practise however, such voltage readings will be only averages For example, instead of a contact drop of one volt at a given point, the actual voltage may be varying from zero to two volts, or possibly from minus one volt to plus three volts These pulsating e.m.fs. will result in high frequency local currents, which have only a harmful influence on the commutation and commutator and brushes These pulsations may be assumed to be roughly related in value to the apparent short circuit volts generated by the armature conductor. In other words, the higher the apparent short circuit volts per conductor, the larger these pulsations are liable to be As the currents set up by these pulsations must be limited largely by the brush contact resistance, it is obvious that there is a limit to the pulsations in voltage, beyond which the current set up by them may be harmful. A very crude practise, and yet possibly, the only fairly safe one, has been to set an upper limit to the apparent short circuit volts per bar, this limit varying to some extent with the conditions of service, such as high peak loads of short duration, overloads of considerable period, continuous operation, etc. Experience has shown that in commutating pole machines, the apparent short circuit voltages per turn may be as high as four to four-and-one-half volts, with usually but small evidence of local high frequency currents, as indicated by the condition of the brush face. If this polishes brightly, and the commutator face does not tend to " smut," then apparently the local currents are not excessive. However, in individual cases, the above limits have been very considerably exceeded in continuous operation, while, in exceptional cases, even with apparently well proportioned commutating poles, there has been evidence of considerable local current at less than four volts per bar.

The contact drop between brush and commutator with the usual brushes is about 1 to 1.25 volts As is well known, this drop is not directly proportional to the current, but increases only slowly with very considerable increases in current density at the brush contact For instance, with 20 amperes per sq in. in a given brush, the contact drop may be one volt; at 40 amperes per square inch, it may be 1 25 volts, while at 100 amperes per square inch, it may be 1 4 volts, and, with materially higher currents, it may increase but little further. This peculiar property of the brush contact is, in some ways, very much of a disadvantage For instance, if the local currents are to be limited to a comparatively low density, then necessarily the voltages generating such currents must be kept comparatively low With the above brush contact characteristics, two volts would allow a local current of 20 amperes per square inch to flow, (there being one volt drop from brush to commutator and one volt back to the brush) If, however, the local voltage is three volts instead of two, or only 50 per cent higher, then a local current of possibly 150 to 200 amperes per square inch may flow, and this excessive current density may destroy the brush contact, as will be described later

It may be assumed in general that the lower the apparent short circuit voltage per armature conductor, the lower the pulsations in this voltage are liable to be. Assuming therefore, as a rough approximation a 50 per cent pulsation as liable to occur, then, from the standpoint of brush contact drop, the total apparent voltage of the commutated coil in continuous service machines should not be more than 4 to 4½ volts, which accords pretty well with practise. For intermittent services, such as railway, materially higher voltages are not unusual

As the main advantage of the carbon brush is that it determines or limits the amount of short circuit current, it might be questioned whether such advantage might not be carried much further by using higher short circuit voltages and proportionately greater resistance. However, there are reasons why this cannot be done The carbon brush is a resistance in the path of the local current, but it is also in the path of the work current As the brush resistance is increased, the greater is the short circuit voltage which can be taken care of with a given limit in short circuit current, but at the same time, the loss due to the work current is increased. Decreasing the resistance of the brush contact increases the loss due to the short circuit current, but decreases

that due to the work current. Thus in each individual case, there is some particular brush resistance which gives minimum loss However, this may not always be the resistance desired for best commutation, from the operating standpoint, but these two conditions of resistance appear to lie fairly close together Practise is a continual compromise on this question of brush contact resistance In some machines, a low resistance brush is practicable, with consequent low loss due to work current. In other cases, which, to the layman, would appear to be exactly similar, higher resistance brushes give better average results Thus one grade of carbon brush is not the most suitable for different machines unless they have similar commutating conditions However, it is impracticable to design all machines of different speeds, types, or capacities so that they will have equal commutating characteristics In non-commutating pole machines where only average commutating fluxes are obtainable, the resistance of the brush is usually of more importance than in the commutating pole type, for, in the latter, a means is provided for controlling the value of the short circuit current However, advantage has been taken of this latter fact to such an extent in modern commutating pole machines, that the critical or best brush resistance has again become a very important condition of design and operation

"Apparent" Short Circuit e m f per Brush. The preceding considerations lead up to another limitation, namely, the total e m f short circuited by the brush. This again may be considered as being made up of two components,—the apparent short circuit e.m f per bar times the *average* number of bars covered by the brush, hereafter called "The apparent short circuit e m.f per brush"; and the e.m.f. per bar generated by the commutating field, times the average number of bars covered by the brush

As has been shown, ordinary carbon brushes can short circuit 2 to 2½ volts without excessive local current. Obviously, if the resultant e.m.f. generated in all the coils short circuited by the brush,—that is, the resultant of the short circuit e.m.fs , due to both the armature and the commutating field is much larger than 2½ volts, large local currents will flow. Therefore, in a commutating pole machine, for instance, the strength of the commutating pole field should always be such that it also neutralizes the total short circuit e.m.f. across the brush within a limit represented by the brush contact drop, in order to keep

within the limits of permissible local currents. With very low resistance brushes, the proportioning of the commutating field for neutralization of the apparent brush e.m.f. would have to be much closer than with higher resistance brushes. Moreover, not only should this e.m.f. generated by the commutating flux balance the total short circuit voltage across the brush within these prescribed limits, but these limits should not be exceeded anywhere under the brush.

It might be assumed that if there is a pulsation of two volts per coil, for instance, then the total pulsation would be equal to this value times the average number of coils short circuited. However, this in general is not correct, as the e.m.f. pulsations for the different coils are not in phase, and their resultant may be but little larger than for a single coil

Based upon the foregoing considerations, the limiting values of the apparent brush e.m.f. may be approximated as follows: Assume ordinary carbon brushes with 1 to $1\frac{1}{4}$ volts drop with permissible current densities—that is, with 2 to $2\frac{1}{2}$ volts opposing action as regards local currents. Also, assume, for example, an apparent brush short circuit e.m f. of 5 volts, with brush resistance sufficient to take care of $2\frac{1}{2}$ volts. Then the total e.m f. due to the commutating flux need not be closer than 50 per cent of the theoretically correct value, with permissible local currents. This is a comparatively easy condition, for it is a relatively poor design of machine in which the commutating pole strength cannot be brought within 50 per cent of the right value. Assuming next, an apparent brush e.m.f. of 10 volts, then the commutating pole must be proportioned within 25 per cent of the right value. In practise, this also appears to be feasible, without undue care and refinement in proportioning the commutating field. If this machine never carried any overload, this 25 per cent approximation would represent a relatively easy condition, for experience has shown that proportioning within 10 per cent is obtainable in some cases, which should allow an apparent brush e.m.f. of 25 volts as a limit. However, experience also shows that this latter is a comparatively sensitive condition, which, while permissible on short peak loads, is not satisfactory for normal conditions. Where such close adjustment is necessary to keep within the brush correcting limits, any rapid changes in load are liable to result in sensitive commutating conditions, for the commutating pole flux does not always rise and fall exactly in time with the arma-

ture flux, and thus momentary unbalanced conditions of possibly as high as 10 or 12 volts might occur with an apparent brush e.m.f. of 25 volts Also, very slight saturation in the commutating pole magnetic circuit may have an unduly large influence on unbalancing the e m.f. conditions. In other words, the apparent brush short circuit and neutralizing e.m.fs. must not be unduly high compared with the permissible corrective drop of the brushes Experience shows that an apparent e m.f of 10 volts across the brush in well designed commutating pole machines is usually very satisfactory, while, in occasional cases, 12 to 13 volts allow fair results on large machines, and, in rare cases, as high as 15 to 18 volts has been allowed on small machines at normal rating. However, overloads, in some cases, limit this permissible apparent brush voltage. As a rule, 30 volts across the brush on extreme overload is permissible, but, usually this is accompanied by some sparking, usually not of a very harmful nature if not of too long duration. Under such overload conditions, doubtless unbalancing of three volts or more may be permissible, and thus, with 30 volts to be neutralized, this means about 90 per cent theoretically correct proportioning of the commutating pole flux. Cases have been noted where as high as 35 to 40 apparent brush volts have been corrected by the commutating pole on heavy overloads with practically no sparking. This, however, is an abnormally good result, and is not often possible of attainment. Obviously, with such high voltages to be corrected, any little discrepancies in the balancing action between the various e.m.fs. are liable to cause excessive local current flow.

Incidentally, the above indicates pretty clearly why d-c generators are liable to flash viciously when dead short circuited. The ordinary large capacity machine can give 20 to 30 times rated full load current on short circuit. If this large current flows, then, neglecting saturation, the armature short circuit e.m.f. across the brush will be excessive. Assuming, for instance, a 10-volt limit for normal rating, then with only ten times full load current, the apparent short circuit e.m f would be 100 volts. The commutating pole, in the normal construction, does not have flux margin of 10 times before high saturation is reached, and in consequence, it may neutralize only 50 to 60 volts of the 100. Therefore a resultant actual e.m.f of possibly 40 volts must be taken care of by the brushes This means an enormous short circuit current in addition to

the 10 times work current. Vaporization of the copper and brushes occurs and flashing results, as will be described more fully in the treatment of flashing limits.

Brush contact drops of 1 to 1.5 volts have been assumed in the preceding, and certain limits in the apparent short circuit e.m.f. based on these drops, have been discussed. However, the conditions may be modified to a considerable extent by effects of temperature upon the brush contact resistance. Usually it has been assumed that the well known decrease in contact resistance of carbon and graphite brushes with increase in temperature, is in some ways related to the negative temperature coefficient of carbon and graphite The writer has been among those who advanced this idea, but later experience, based upon tests, has shown that the reduced drop with increase in temperature does not necessarily hold any relation to the negative temperature coefficient of the carbon brush itself, for similar changes in the contact drop have been found with materials, other than carbon, which actually had, in themselves, positive temperature coefficients. Moreover, in some tests, the changes in contact resistance with increase in temperature have proved to be much greater in proportion than occurs in the carbons themselves. In some cases, the measured drops with temperature increases of less than 100 deg. cent decreased to one-half or one-third of the drops measured cold

Obviously, these decreased contact resistances or drops may have a very considerable effect on the amount of local current which can flow and, therefore, in such case the foregoing general deductions, should be modified accordingly However, the results are so affected by the oxidation of the copper commutator face, and other conditions also more or less dependent upon temperature, that, as yet, no definite statement can be made regarding the practical effects of increase in temperature except the general one that the resistance is usually lowered to a considerable extent Apparently, oxidation of the copper face tends toward higher contact resistance Ofttimes, "sanding off" the glaze tends to give poorer commutation The above points to one explanation of this

Assuming any desired limits for the apparent e m fs, such as 4 to 4½ volts per commutator bar, it is possible to approximate by calculation the limiting capacities of generators or motors in terms of speed, etc Appendix I shows one method of doing this In the writer's experience, a number of machines have been

carried up to about the limits derived in the appendix, and the practical results were in fair accord with the calculations. In general, it may be said that in large machines, the upper limits of capacity in terms of speed, etc. are so high that they do not indicate any great handicap on future practise.

In the foregoing, the limits for the apparent short circuit e.m.f. per bar and per brush have been based upon the brush contact resistance. However, it may be suggested that something other than the brush contact resistance might be used for limiting the local current, and thus the commutating limits might be raised. For instance, an armature winding could be completely closed on itself, with high resistance leads carried from the winding to the commutator bars. Each of such leads would be in circuit only where the brushes touched the commutator bars. Thus there could be very considerable resistance in each lead without greatly increasing the total losses; and, unlike the brushes, each lead would be in circuit only for a very small proportion of the time.

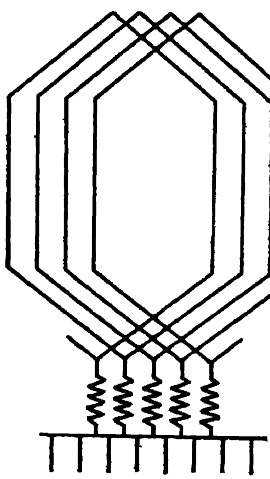


FIG. 1

About 10 years ago, the writer designed a non-commutating pole d-c. turbo-generator with such resistance leads connected between the winding and the commutator. The leads were placed in the armature slots below the main armature winding. The idea was to have enough resistance in circuit with the short circuited coils that the brushes at no load could be thrown well forward into a field flux sufficient to produce good commutation at heavy load, even if very low resistance brushes were used. Tests of this machine showed that the non-sparking range, with the brushes shifted either forward or back of the neutral point was very much greater than in an ordinary machine. In this case, it developed that the leads were of too high resistance for practical purposes, as the armature ran too hot, the heat-dissipating conditions in a small d-c. turbo-armature not being any too good at best. These tests however, indicate one possibility in the way of increasing the present limits of voltage per bar and volts across the brush. Moreover, such resistances can have a positive temperature coefficient of resistance, instead of the

negative one of the carbon brushes and contacts. Also, the corrective action in limiting local currents would vary directly with the current over any range, and not reach a limit, as in carbon brushes

Considerable experience with resistance leads in d-c operation has also been obtained in large a-c. commutator type railway motors, designed for operation on both a-c and d-c. circuits. Apparently these leads have a very appreciable balancing action as regards division of current between brush arms in parallel. With but few brushes per arm, it appears that very high current densities in the brushes can be used without undue glowing or honeycombing. Presumably the reduction in short circuit current, when operating on d-c , also has much to do with this. Some special tests were made along this line, and it was found that a very low resistance in the leads, compared with that which was best for a-c. operation, was sufficient to exert quite a decided balancing between the brush arms

With properly proportioned resistance leads it should be possible to use very low resistance brushes, and relatively high current densities. Advantage of this might be taken in various ways. There may prove to be serious mechanical objections to such arrangements However, if the objections are not too serious, the use of resistance leads in this manner may be practised at some future time as we approach more extreme designs

FLASHING

One of the limits in commutating machinery is flashing. This may be of several kinds. There may be a large arc or flash from the front edge of the brush, which may increase in volume until it becomes a flash-over to some other part of the machine. Again, a flash may originate between two adjacent bars at some point between the brush arms, and may not extend further, or it may grow into a general flashover. Different kinds of flashes may arise from radically different causes, some of which may be normally present in the machine, while others may be of an accidental nature.

Whatever the initial cause, the flash itself means vaporized conducting material. If the heat developed by or in this vapor arc is sufficient to vaporize more conducting material—that is, generate more conducting vapor—then the arc or flash will grow or continue. Thus, true flashing should be associated with vaporization, and, in many cases, in order to get at the initial

cause of flashing, it is only necessary to find the initial cause of vaporization.

Arcs Between Adjacent Commutator Bars. This being one of the easiest conditions to analyze, it will be treated first, especially as certain flashing conditions are dependent upon this.

A not uncommon condition on commutators in operation is a belt of incandescent material around the commutator, usually known as "ring fire" This is really incandescent material between adjacent bars, such as carbon or graphite, scraped off the brush faces usually by the mica between bars. As the mica tends to stand slightly above the copper, due to less rapid "wear," its natural action is to scrape carbon particles off the brush. These particles are conducting and if there is sufficient voltage, and current to bring them up to incandescence, this shows as a streak of fire around the commutator In many cases, by its different intensities around the commutator, this ring fire shows plainly the density of the field flux, or e m.f. distribution around the machine It is practically zero in the commutating or neutral zone, and shows plainly under the main field. In loaded machines, this often indicates roughly the flux distortion. In machines which act alternately as motors and generators, as in reversing mill work, the point of highest incandescence shifts forward or backward over the commutator, depending upon the direction of field distortion.

In undercut commutators (those with mica cut below the copper surface) this ring fire is also observable at times, due to conducting particles in the slots between bars. Usually such particles consist of carbon or graphite, as already stated, but particles of copper may also be present. Also, oil or grease, mixed with carbon, will carbonize under incandescence, and will thus add to the ring fire. Often when a commutator is rubbed with an oiled cloth or wiper, ring fire will show very plainly, and then gradually die down. The burning oil exaggerates the action, and also, the oil itself may enable a conducting coating to adhere to the mica edges, thus starting the action, which disappears when the oil film is burned away. However, when the oil can penetrate the mica, the incandescence may continue in spots and at intervals, the mica being calcined or burned away so that it gradually disppears in spots. This is the action usually called "pitting", which experience has shown to be almost invariably caused by conducting material in the mica, such as carbonized oil, carbonized binding material, copper and carbon particles which have been carried in with the oil, etc.

This ring fire is not always a direct function of the voltage between bars, although, under exactly equivalent conditions of speed, grade of brushes, etc., it is closely allied with voltage conditions. In high voltage machines, usually hard high-resistance brushes are used, which tend to give off the least carbon in the form of particles; while in low voltage machines, soft, low-resistance brushes, with a good percentage of graphite in them, are common, and these naturally tend to coat the mica to a greater extent.

Under extreme conditions, this ring fire may become so intense locally that there is an actual arc formed between two adjacent bars, due to vaporization of the copper. This may show in the form of minute copper beads at the edge of the bar, or minute "pits" or "pockets" may be burned in the copper next to the mica. In extreme cases, where the voltage between bars is sufficient to maintain an arc, conical shaped cavities or holes may be burned in the copper. In such cases, the arc is usually explosive, resembling somewhat a small "buck-over." An examination of the commutator will show melted-out places, as in Fig. 2. Part of the missing copper has been vaporized by the arc, while part may have become so softened or fused that it is thrown off by centrifugal force. Experience shows that sometimes these explosive arcs grow into general flashes, while at other times, they are purely local.

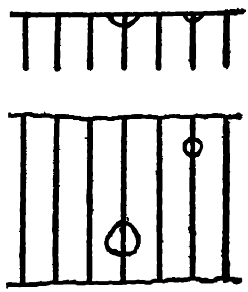


FIG. 2

An extended study was made of such arcs to determine the conditions which produced them. Also, numerous tests were made, the results of which are given below.

It was determined first, that these explosive arcs between adjacent bars were dependent, in practically all cases, upon a fairly high voltage between bars. This was reasonable to expect, but it was found that the voltage between bars which would produce arcs in one case, would not do so in another. Apparently there were other limiting or controlling conditions. It developed that the resistance of the armature winding between two adjacent bars has much to do with the arc. Apparently an excessive current is necessary to melt a small chunk out of a mass of good heat-conducting material like a large copper commutator; and also, a certain amount of time is required to bring it up to the

melting point Therefore, both time and current are involved, as well as voltage. A series of tests was made to determine some of the limiting conditions.

The commutator of a small machine (about 20 kw., high speed) was sprinkled with iron filings, fine dust, etc. during several days' operation under various conditions of load, field distortion, etc. Such dust, whether conducting or not, apparently would not cause arcing between bars. Graphite was finally applied with a special "wiper," and with this, small arcs or flashes could be produced at 50 to 60 volts maximum between commutator bars. It soon became evident that this was too small a machine from which to draw conclusions. Then numerous other much larger generators were tested A slow-speed engine type generator of 200-kw. capacity at 250 volts, was speeded up to about double speed, in order to obtain sufficiently high e.m.f. between commutator bars. With a clean commutator nothing was obtained at 40 volts maximum per bar. The commutator was then wiped with a piece of oily waste which had been used to wipe off other commutators. Arcs then occurred repeatedly between commutator bars, although all such arcs were confined to adjacent bars and there were no actual flashovers from brush holder to brush holder. Moreover, the arcs always appeared to start about midway between brush arms or neutral points, and lasted only until the next neutral point was reached. Quite large pits or cavities were burned in the bars next to the mica, as shown in Fig. 2. some of these being possibly $\frac{1}{4}$ inch in width, and 1/16 inch deep or more at the center This indicated excessively large currents. These arcs would develop at about 32 to 34 volts between bars, and they were very vicious (explosive) above 35 volts

Still larger machines were tested with various speeds, voltage between bars, etc It was found that, as a rule, the larger the machine—or rather, the lower the resistance of the armature winding per bar—the lower would be the voltage at which serious arcing would develop In these tests, it was found that graphite mixed with grease gave the most sensitive arcing conditions.

In these various tests, no arcing between bars was developed in any case at less than 28 volts maximum, while 30 volts was approximately the limit on many machines. However, the results varied with the speed Apparently it took a certain time to raise the incandescent material to the arcing point and to build up a big arc. Therefore, the duration of the possible arcing period appeared to be involved. If this were so, then a higher

voltage limit for a shorter time should be possible with the same arcing tendency. Also, if this were the case, then with 30 volts maximum, for instance, between commutator bars with an undistorted field flux, the arcing should be the same as with a somewhat higher voltage with a highly distorted narrow peaked field. In other words, the limiting voltage between bars on a loaded machine might be somewhat higher than on an unloaded machine. This was actually found to be the case, the difference being from 10 per cent to 15 per cent in several instances. This, however, depended upon various limiting conditions such as the actual period within which the arc could build up to a destructive point, etc.

One very interesting case developed which apparently illustrated very beautifully the effects of lengthening or shortening the period during which the arc could occur. A high-speed, 600-volt generator of a motor-generator set was speeded up about 60 per cent above normal. Even at normal speed this was a rather high-frequency machine, so that the period of time for a commutator bar to pass from neutral point to neutral point was very short. At the highest speed the graphite-grease was used liberally on the commutator, but without causing arcing, even when the voltage was raised considerably higher than usually required for producing arcs between bars in other machines of similar size. Neither was there much ring-fire at the highest speed with normal voltage. Finally, after an application of graphite, without forming arcs or unusual ring-fire, the speed was reduced gradually with normal voltage maintained. The ring-fire increased with decrease in speed, until at about normal speed, it was so excessive that the on-lookers expected an explosion of some sort. However, the voltage was now below the normal arcing point and nothing happened. At still lower speed, but with reduced voltage on account of saturation, the ring-fire gradually decreased. Apparently at the very high speeds, the time was too short for the ring-fire to reach its maximum; while with reduction in speed, even with somewhat reduced voltage, the ring-fire increased to a maximum and then decreased. This test was continued sufficiently to be sure that it was not an accidental case. Only a certain combination of speed, frequency, voltage, etc. could develop this peculiar condition, and it was purely by accident that this combination was obtained, for the result was not foreseen in selecting the particular machine used.

A summation of these and other tests led to the conclusion that there were pretty definite limits to the maximum volts per bar, beyond which it was not safe to go. These limits however, involved such a number of conditions that no fixed rule could be established, and apparently, the designer has to use his judgment and experience to a certain extent, if he works very close to the limits. The grades and materials of the brushes, the thickness of the mica, flux distortion from overloads, etc. must be taken into account. For instance, the above tests were made on machines with 1/32-inch mica between bars. This thickness is fixed, to a great extent, in non-undercut commutators, by conditions of mica wear, as will be referred to later. But with undercut commutators, thicker mica can be used, and, while the gain in permissible safe voltage between bars is not at all in proportion to the mica thickness, yet it is enough to deserve consideration.

The general conclusions were that with 1/32-inch mica, large current machines would very rarely flash with 28 volts *maximum* between bars; while with moderate capacities, 30 volts is about the lower limit; and with still smaller machines, 100 kw. for example, this might be as high as 33 to 35 volts, the limit rising to 50 or 60 volts with very small machines.

Of course, the brush conditions have something to do with the above limits, and many exceptions to these figures will be found in actual practise. Many machines are in daily service which are subject to more or less ring-fire, but which have never developed trouble of any sort, and doubtless never will. Apparently, ring-fire in itself is not harmful, as a rule. It is only where it starts some other trouble that it may be considered as actually objectionable.

The above limiting figures are interesting when compared with the voltages necessary to establish arcs in general. An alternating arc through air will not usually maintain itself at less than some limiting voltage such as 20 to 25 volts, corresponding to peak values of 28 to 35 volts. Moreover, an arc formed between the edges of two insulated bodies, such as adjacent commutator bars, will naturally tend to rupture itself due to the shape of its path. Furthermore, the resistance and reactance of the short circuited path, while comparatively low in large machines, will tend to limit the voltage which maintains the arc. In small machines with relatively high internal drops in the short circuited coils, the current will not reach a

commutator vaporizing value unless the initial voltage between bars is comparatively high, and usually the explosive actions are relatively small, and, in many cases, no serious arcs will develop at all. Obviously, the less the local current can increase in the case of short circuits between adjacent bars, the higher the voltage between bars can be, without danger. In machines having *inherent constant current characteristics*, very high voltages between adjacent commutator bars are possible without serious flashing or burning. In consequence, from the flashing standpoint, constant current machines can be built for enormously high terminal voltages, compared with constant potential machines. This is a point which is very commonly overlooked in discussing high-voltage d-c. machines.

Coming back to the subject of arcs between commutator bars, these are more common than is usually supposed, for, in many cases, the operating conditions are such that these arcs, if very small, or limited, will show no visible evidence. Only very minute particles of copper may be vaporized. However, these minute arcs may sometimes lead directly to more serious flashing. If, for instance, they occur in proximity to some live part of the machine, such as an over-hanging brush holder which is at a considerable difference of potential from the arcing part of the commutator, the conducting vapor may bridge across and start a big arc or flash. In one instance, which the writer has in mind, a very serious case of trouble occurred in this way. This was a very large capacity 250-volt, low-speed, generator, in which the maximum volts per bar were not unduly high. When taking the saturation curve in the shop test, this machine "bucked" viciously several times, apparently without reason. An investigation of the burning indicated a possible source of trouble. The brush holder arms or supports to which the individual holders were attached, were located over the commutator about midway between neutral points, and, about one inch from the commutator face. This was not the normal position of the brush arms, as a temporary set of holders was being used for this test. It was noted that just before the flashovers occurred, considerable ring-fire developed. The conclusion was drawn from all the evidence that could be obtained, that a small arc had formed between bars that had reached to the brush arms, thus short circuiting a high enough voltage to draw a real flash. This happened not once but several times. The proper holders

were then applied, which put the brush arms in a much less exposed position, and not a single flashover occurred in all the subsequent tests and operation. In another case, a large synchronous converter carrying full load on shop test flashed over a number of times, apparently without sufficient cause. The commutation was perfect, as evidenced by the fact that there was no perceptible sparking. The maximum voltage between bars was comparatively low. At first the flashovers were blamed on drops of water from the roof of the building, but this theory was soon disproved. An examination of the brush holders showed that certain live parts, fairly close to the commutator, were at a considerable difference of potential from the nearest part of the commutator. There was but little ring-fire on the commutator, and therefore, minute arcs at first were not blamed for the trouble. A modified brush holder was tried however, with a view to decreasing the high difference of potential between the live parts. All flashing then disappeared and no trouble of this sort was ever encountered in a large number of duplicate machines brought through afterwards. Both the above cases should be considered as abnormal, and they have been selected simply as examples of what small arcs between bars may do. These two cases do not in themselves constitute a proof of this action, but they serve to verify other evidences which have been obtained.

In view of the fact that small arcs of a non-explosive sort may form at voltages considerably lower than the limits given in the preceding part of this paper, it should be considered whether such small arcs can cause any trouble if no other live parts of the machine are in close proximity. One case should be considered, namely, that of other commutator bars adjacent to the arc. When conducting vapor is formed by the first minute arc, this vapor in spreading out may bridge across a number of commutator bars having a much higher total difference of potential across them than that which caused the initial arc. Assume, for instance, a very crowded design of high-voltage commutator. In some cases, in order to use high rotative speeds, without unduly high commutator peripheral speed, the commutator bars are sometimes made very thin and the volts per bar very high, possibly up almost to the limit. Assuming a thickness of bar and mica of 0.2 inch (or 5 bars per inch) and a maximum volts per bar of 25, then there is an e.m f. of 125 volts *per inch* circumference of the commutator. In such

case, a small arc between two bars may result in bridging across a comparatively high voltage through the resulting copper vapor Therefore, when considering the possible harmful effects of minute arcs, the volts per inch circumference of the commutator should be taken into consideration. The writer observed one high-voltage commutator which flashed viciously at times, apparently without "provocation" The only explanation he could find was that the vapor from little arcs resulting from ringfire was sufficient to spread all over the commutator, the bars being very thin and the voltage per bar very high. However, difficulties from this cause have not yet become serious, probably because no one has yet carried such constructions to the extreme, in practical work

High voltage between commutator bars may result in flashing due to other than normal operating conditions. Excessive overloads may give such high voltages per armature coil or per commutator bar, immediately under the brush, that the terrific current rush will develop conducting vapors under the brush, which appear immediately in front of the brushes, as such vapors naturally are carried forward by rotation of the commutator. This short circuit condition under the brush has already been referred to when treating of commutation limits It was shown then that an inherent short circuit voltage of 4 to 4½ volts is permissible in good practise Immediately under the commutating pole this voltage is practically neutralized by the commutating pole field, but immediately ahead or behind the pole it is not neutralized usually, except to the extent of the commutating pole flux fringe. Thus, the resultant voltage between two bars a little distance ahead of the brush, is liable to be considerably higher than under the brush Assuming, for instance, 3½ volts per bar, due to cutting the resultant field just ahead of the brush, then with 10 times full load current, for example, there would be 35 volts between bars, and this is liable to be accompanied by highly conducting vapor formed by the excessive current at the brush contact, this vapor being carried forward by rotation of the commutator. Here are the conditions for a flash, which may or may not bridge across to some other live part If the current rush is not too great, this flash will usually appear only as a momentary blaze just in front of the brush. In many cases, if this blaze or heavy arc were not allowed to come in contact with, or bridge between, any parts having high difference of potential, it would not be

particularly harmful. In case of "dead short circuiting" of large moderately high-voltage machines where the current can rise to 25 or 30 times normal, it is astonishing how large such arcs or flashes may become, and to what distances they will reach. The arc will sometimes go in unanticipated directions. The conducting vapor may be deflected by magnetic action and by air drafts Shields or partitions will sometimes produce unexpected results, not necessarily beneficial. Unless such shields actually touch the commutator face so that conducting vapor cannot pass underneath them, the vapor that does pass underneath may produce just as harmful results as if the shields were not used. Trying to suppress such arcs by covers or shields is very much the case of damming a river at the wrong end in order to prevent high water

From the preceding considerations it would appear that a compensated direct-current machine should have some advantages over the straight commutating-pole type in case of a severe short circuit. With the lesser saturation in the commutating pole circuit due to the lower leakage, the apparent armature short circuit e.m.f. will usually be better neutralized under extreme load conditions, and thus there will be lower local currents in the brush contacts In addition, the armature flux will be practically as well neutralized behind and ahead of the brush, as it is under the brush, so that, with ten times current as in the former example, there may be only a low e.m.f. per bar ahead of the brush, instead of the 35 volts for the former case Obviously, the initial flashing cause, and the tendency to continue it ahead of the brush, will be materially reduced. The compensating winding is therefore particularly advantageous in very high voltage generators, in which the bars are usually very thin and the maximum volts per bar are high.

There is a prevailing opinion that when a circuit breaker opens on a very heavy overload or a short circuit, flashing is liable to follow from such interruption of the current In some cases, this may be true However, when a breaker opens on a short circuit, it is difficult for the observer to say whether both the opening of the breaker and the flash are due to the excessive momentary current, or one is consequent to the other. The short circuit, if severe, will most certainly cause more or less of a flash at the brush contacts by the time the breaker is opened, and if this flash is carried around the commutator, or bridges

across two points of widely different potentials, then it is liable to continue after the breaker opens, and thus gives the impression that the flashing followed the interruption of the circuit. In railway and in mine work in particular, a great many flashes which are credited to overloads are primarily caused by partial short circuits on the system, or "arcing shorts," which are extinguished as soon as the main breakers are opened, so that but little or no evidence of any short circuit remains. Such a partial short circuit however, may be sufficient to open the generator circuit and to cause a flash at the same time. Not infrequently, such flashes are simply credited to opening of the breakers

There are other conditions, however, where a flash is liable to result directly from opening the breaker on heavy overload. If as referred to before, the apparent short circuit e m.f. per brush on heavy overload is from 25 to 35 volts, then if the armature magnetomotive force could be interrupted suddenly, with a correspondingly rapid reduction in the armature flux, while the commutating field flux does not die down at an equally rapid rate, then momentarily, there will be an actual short circuit voltage of a considerable amount under the brushes which may be sufficient to circulate large enough local currents to start flashing. With commutating pole machines, this condition may result from the use of solid poles and solid field yokes Laminated commutating poles are sometimes very much of an improvement. However, the yokes of practically all direct current machines are of solid material, and thus tend to give sluggishness in flux changes. The above explains why non-inductive shunts, or any closed circuits whatever, are usually objectionable on commutating poles or their windings.

In non-commutating pole machines, where the brushes are liable to be shifted under the main field magnetic fringe in order to commutate heavy loads, flashing sometimes results, when such heavy overload is interrupted.

Also, if the rupture of the current is very sudden, there will be an inductive "kick" from the collapse of the armature magnetic field. This rise in voltage sometimes is sufficient to start a flash, especially in those cases where flashing limits are already almost reached.

In synchronous converters, the conditions are materially different from d-c. generators as regards flashing when the load is suddenly broken. In such machines, the flash is liable

to follow the opening of the breaker, if simply a heavy overload is interrupted. This is possibly more pronounced in the commutating pole machine than in the non-commutating pole type In a commutating pole converter, the commutating pole magnetomotive force is considerably larger than the resultant armature magnetomotive force, under normal operating conditions, but is much smaller than the armature magnetomotive force considered as a straight d-c. or a-c. machine. Normally the commutating pole establishes a commutating field or flux in the proper direction in the armature. However, if, for any reason, the converter becomes a motor or a generator, even momentarily, the increased magnetomotive force of the armature may greatly exceed that of the commutating pole, so that the commutating pole flux will be greatly increased, or it may be greatly reduced, or even reversed, depending upon which armature magnetomotive force predominates.

The above is what happens when a synchronous converter hunts, and under the accompanying condition of variable armature magnetomotive force, the commutating pole converter, with iron directly over the commutating zone, is liable to show greater variations in the flux in the commutating zone than is the case in the non-commutating pole converter. Experience has shown that when a synchronous converter carrying a heavy overload has its direct-current circuit suddenly interrupted, it is liable to hunt considerably for a very short period, depending upon the hunting constants of the individual machine and circuit. Apparently, all converters hunt to some extent with such change in load. This hunting means wide variations in the commutating pole flux with corresponding sparking tendencies. For a "swing" or two, this sparking may be so bad as to develop into a flash. Thus the flash follows the interruption of the circuit.

Curiously, the most effective remedy for this condition is one which has proved most objectionable in d-c. machines, namely, a low-resistance closed electric circuit surrounding the commutating pole. The primary object of this remedy is not to form a closed circuit around the commutating field, but to obtain a more effective damper in order to minimize hunting. In a paper presented before the Institute several years ago,* the writer showed that the ideal type of cage winding for damp-

*Commutating Poles in Synchronous Converters. Page 171.

ing synchronous converters, namely, that in which all circuits are tied together by common end rings, was not suitable for commutating pole converters due to the fact that the various sections of this cage winding form low-resistance closed circuits around the commutating poles. This was in accord with all evidence available to that time, and no one took exception to it However, later experience has shown that this was incorrect, for, in later practise, it was found that the use of a complete cage damper of low resistance which decreases the hunting tendency, also greatly decreases the flashing tendency, so that today most converters of the commutating pole type are being made with complete cage dampers. Apparently, the flashing tendencies in converters due to hunting are much worse than those due to flux sluggishness. Therefore, a sacrifice can be made in one for the benefit of the other.

In the case of a dead short circuit on the d-c side of a synchronous converter, there is liable to be flashing, just as in the d-c machine, and the flash and the breaker opening are liable to occur so closely together that an observer cannot say which is first.

In d-c. railway motors, flashing at the commutator is not an uncommon occurrence One rather common cause of flashing, especially at high speed, is due to jolting the brushes away from the commutator, due to rough track, etc This is especially the case with light spring tension on the brushes. The carbon breaks contact with the copper, forming an arc which is carried around. Another prolific source of flashing is due to opening and closing the motor circuit in passing over a gap or dead section in a trolley circuit Here the motor current is entirely interrupted, and, after a short interval, it comes on again, without any resistance in circuit except that of the motor itself. If the current rush at the first moment of closing is not too large, and if the armature and field magnetic fluxes build up at the same rate, then there is usually but small danger of a flash, except under very abnormal conditions. The rapidly changing field flux however generates heavy currents under the brushes, thus tending toward flashing. The reactance of the motor, especially of the field windings, limits the first current rush to a great extent. According to this, closed secondary circuits of low resistance around either the main poles or the commutating poles, should be objectionable, and experience bears this out

In railway armatures, as a rule, fewer commutator bars per pole are used on the average than in stationary machines of corresponding capacity, except possibly, in large capacity motors. This is due largely to certain design limitations in such apparatus, but this has doubtless been responsible for a certain amount of flashing in such apparatus

Average e.m.f. and "Field Form." A rather common practise has been to specify the average volts per bar in a given machine. This, in itself, does not mean anything, except in a very general way; for the limit is really fixed by the maximum volts per bar, as already shown, and there is no fixed relation between the average and the maximum volts per bar. The ratio between these two voltages is dependent upon the field flux distribution,—that is, the "field form." In practise, this ratio varies over a wide range, depending upon the preferences of the designer, upon limitations of pole space available, etc. Also, with load, it depends upon the amount of flux distortion of the field, which, in turn varies greatly in practise. In well proportioned modern machines, where space and other limitations permit, the average e.m.f. per bar is about 70 per cent of the maximum at no load, and about 55 per cent to 60 per cent with heavy load. This means that about 15 volts per bar, average, is the maximum permissible, in large machines with considerable field distortion, if a maximum of 28 volts per bar is not to be exceeded. On this basis, a 600-volt machine should therefore have not less than 40 commutator bars per pole. However, this is with considerable field distortion. If this distortion is reduced or eliminated, the average volts can be considerably higher, as in machines with high saturation in the pole faces, pole horns and armature teeth, or with compensated fields. Synchronous converters are practically self-compensated and can therefore have higher limits than the above, if the normal rated e.m.f. is never to be exceeded. However, in 600-volt converter work, in particular, wide variations sometimes momentarily occur, up to 700 to 750 volts, and such machines should have some margin for such voltage swings. The ordinary 600-volt d-c. generator also attains materially higher voltages at times, which would be taken into account in the limiting voltage per commutator bar and the total number of commutator bars per pole.

Obviously, the "fatter" the field form, the nearer the average voltage can approach the maximum. With an 80 per cent

field form, instead of 70 per cent, for instance, the number of bars per pole can be reduced directly as the polar percentage is increased; and 35 bars per pole with 80 per cent would be as good as 40 bars with 70 per cent assuming the same percentage of field distortion in both cases. An increase in the polar arc will tend toward increased distortion, but the reduced number of turns per pole should practically balance this, so that, other things being unchanged, the flux distortion should have practically the same percentage as before.

In large machines of very high speeds, large polar percentages, —that is, large "field form constants," are very advantageous, but are not always obtainable, due to the space required for the commutating pole winding. In compensated field machines, with their smaller commutating pole windings, the conditions are probably best for high field form constants, and high average volts per bar; and thus this type often lends itself very well to those classes of machines where the minimum possible number of commutator bars is necessary. This is the case with very high speeds, and also for very high voltage machines.

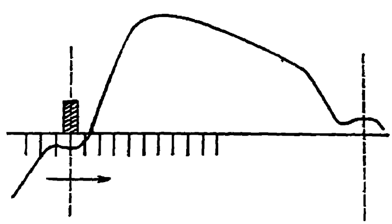


FIG. 3

Usually it is considered that the commutating conditions of a machine are practically the same with the same current, whether it be operated as a generator or motor. However, when it comes to flashing conditions, there is one very considerable difference between the two operations. In the d-c. generator, the field flux distortion by the armature is such as to crowd the highest field density, and thus the highest volts per bar, away from the forward edge of the brushes. In the motor, the opposite is the case, and therefore there is a steeply rising field, and a corresponding e.m.f. distribution in front of the brushes. As the flash is carried in the direction of rotation it may be seen that, in this particular, the generator and motor are different.

BLACKENING AND BURNING—HIGH MICA—"PICKING UP" COPPER

In the preceding, certain limitations of commutation and flashing have been treated. There are, in addition, a number

of other conditions which are related closely to commutation, and which have already been touched upon to a limited extent. One of these is the permissible current density in the brushes or brush contacts.

As brought out before, there are two currents to be considered, namely, the work current which flows to or from the outside circuit, and the local or short circuit current which is purely local to the short circuited coils and the brush. The *true* current density is that due to the actual resultant current in the brush tip or face, which is very seldom uniform over the whole brush tip. The " apparent " current density is that due to the work current alone—assumed to be uniform over the brush tip. The current density very commonly has been assumed as the total work current, in and out, divided by the total brush section, and, moreover, this has been considered as the true current density, the local or short circuit currents being neglected altogether. This method of considering the matter has been very misleading, resulting in many cases, in a wrong or unsuitable size of brush being used just to meet some specified current density. In many of the old, non-commutating pole machines, the local currents were predominant under certain conditions of load, for the brushes, as a rule, had to be set at the best average position, so that at some average load, the commutating conditions would be best. At higher and lower loads, the short circuit currents were usually comparatively large. The wider the brush contact circumferentially, the greater would be the short circuit currents and the higher the actual current density at one edge of the brush, while the apparent density would be reduced. Thus, in attempting to meet a low specified current density, the true density would be greatly increased. The fallacy of this procedure was shown in many cases in which the brush contact was very greatly reduced by grinding off one edge of the brush. Very often, a reduction in circumferential width of contact to one-half resulted in less burning of the brush face. The apparent density was doubled but the actual maximum density was actually reduced. Many of these instances showed very conclusively that much higher true current densities were practicable, provided the true and apparent densities could be brought more nearly together. This is what has been accomplished to a considerable extent in the modern well designed commutating pole machine. In such machines, the current dis-

tribution at the brush face is nearly uniform under all conditions of load It is not really uniform, even in the best machines; but the variations from uniformity, while possibly as much as 50 per cent in good machines, is yet very small compared with the variation in some of the old non-commutating pole machines. In consequence, it has been possible to increase the apparent current densities in the brushes in modern commutating pole machines very considerably above former practise, while still retaining comparatively wide brush faces. In fact, the width of the brush contact circumferentially is not particularly limited if the commutating field flux can be suitably proportioned; that is, where a suitable width and shape of commutating field can be obtained. In many of the old time machines, an apparent density of 40 amperes per square inch under normal loads was considered as amply high, while at the present time, with well proportioned commutating poles, 50 per cent higher apparent densities are not uncommon However, experience shows that the same brushes, with perfectly uniform distribution of current at the brush face, can carry still higher currents. Therefore, in modern commutating pole machines, the actual upper limit of brush capacity is not yet attained. But there are reasons why this upper limit is not practicable. One reason is that already given, that uniform current distribution over the brush face is seldom found. This means that a certain margin must be allowed for variations. A second reason lies in the unequal division of current between the various brushes and brush arms. This may be due initially to a number of different causes. However, when a difference in current once occurs, it tends to accentuate itself, due to the negative coefficient of resistance of the carbon brushes and brush contacts. If one of the brushes, for instance, takes more than its share of current for a period long enough to heat the brush more than the others, then its resistance is lowered and it tends to take still more current. If there were no other resistance in the current path, it is presumable that the parallel operation of carbon brushes would be more or less unsatisfactory. In the practical case, however, instead of the operation being impracticable, it is merely somewhat unstable. Unequal division of current between the brushes on the same brush arms, is to some extent, dependent upon the total current per arm. Where there are many brushes in parallel and the total current to be carried is very large, it is obvious that one brush may take

an excessively large current without materially decreasing the current carried by the other brushes. As a rule, the larger the current per arm, the more difficult is the problem of properly balancing or distributing the current among all the brushes. Schemes have been proposed, and patented, for forcing equal division, but, as a rule, they have not proved very practicable, although some comparatively simple expedients have been tried out with a certain degree of success.

In the same way, the division of current among brush arms of the same polarity is not always satisfactory. 50 per cent variation of current between different arms is not very unusual, and the writer has seen a number of instances where the variation has been 100 per cent, or even much more. Obviously, with such variation, it is not practicable to work the brushes up to the maximum density possible, for some margin must be allowed for such unbalancing.

Experience has shown that when current passes through a moving contact, as from a brush to the commutator copper, or *vice versa*, a certain action take place which resembles electrolytic action to some extent, although it is not really electrolytic. It might also be said to resemble some of the actions which takes place in an arc. Minute particles appear to be eaten or burned away from one contact surface, and these are sometimes deposited mechanically upon the opposing surface. The particles appear to be carried in the direction of current flow, so that if the current is from the carbon brush to the copper, the commutator face will tend to darken somewhat, evidently from depositation of carbon. If the current is from the copper to the carbon, the brush face will sometimes tend to take a coating of copper, while the commutator face will take a clean, and sometimes raw, copper appearance. As the current is in both directions on the ordinary commutator, this action is more or less averaged, and therefore is not usually noticed. With one polarity or direction of current, the commutator face eats away, while with the other direction, the brush face is eaten away and may lose its gloss.

The above action of the current gives rise to a number of limiting conditions in direct-current practise. Experience shows that this " eating away " action occurs with all kinds of brushes, and with various materials in the commutator. It appears to be dependent, to a considerable extent, upon the losses at the contact surface. In other words, it is dependent upon both the

current and the contact drop. With reduction in contact drop, this burning action apparently is decreased, but in commutating machinery. this reduction cannot be carried very far, in most cases, on account of increase in short circuit current, which nullifies the gain in contact drop. In fact, in each individual machine, there is some critical resistance which gives least loss and least burning at the contact surfaces.

Practise has shown that this burning action is very slow at moderate current densities in carbon and graphite brushes—so slow as usually to be unnoted. However, if the actual current density in the brush face is carried too high, the burning of the brushes may become very pronounced. With the actual work current per brush usual in present practise, the burning of the brush face may usually be credited to local currents in the brushes This is one pretty good indication of the presence of excessive local currents. It also indicates the location and direction of such currents, but is not a very exact quantitative measure of them. It is not uncommon, in examining the brushes of a generator or motor, to find a dull black area under one edge of the brush, which obviously has been burned, while the remainder of the brush face is brightly polished. In severe cases, practically as good results will be obtained if the burned area is entirely cut away by beveling the edge of the brush.

This eating away of either the brush face or the commutator, and the deposit upon the opposing face, leads to certain very harmful conditions in direct-current machinery. As stated before, if the true current density is kept sufficiently low in the contact face, the burning is negligibly small in most cases. However, where the current passes from the commutator to the brush, it is the commutator copper which eats away, while the mica between commutator bars does not eat away, but must be worn away at the same rate that the copper is burnt, if good contact is to be maintained. Let the burning of the copper gain ever so little on the wear of the mica, then trouble begins. The brush begins to "ride" on the mica edges and does not make true contact with the copper. This increases the burning action very rapidly, so that eventually the mica stands well above the copper face. This is the trouble usually known as "high mica." It is frequently credited to unequal rates of wear of copper and mica. This idea of unequal wear has been partly fostered by the fact that with relatively thick

mica, the action is greatly increased, or, with very thin commutator bars, with the usual thickness of the mica, the high mica trouble becomes more serious. In both these latter cases, it is the higher percentage of mica,—that is, the relatively poorer wearing characteristics of the mica itself, which is at fault. But the commutator copper does not *wear away.* In fact, it is not physically possible for it to *wear* below the mica. It is "eaten away" or burned, as described above. In some special cases, where this burning is unusually severe, the mica apparently wears down about as fast as the copper, so that the commutator remains fairly clean and has no particularly burnt appearance, but grooves or ridges, showing undue wear. But this rapid apparent wear is a pretty good indication that excessive burning action is present at times, usually due to excessive local currents. In some cases, this burning action may be present only during heavy or peak loads which may be so interspersed with periods of light running that the true wear of the mica catches up with the burning of the copper. In such cases, the commutator may have a beautiful glossy appearance normally, but may wear in grooves and ridges On account of this burning action, practise has changed somewhat in regard to staggering of brushes on commutators to prevent ridging between the brushes. Formerly, it was common practise to displace all the positive brushes one direction axially, and the negatives in the other direction, in order to have the brushes overlap. This, however, did not entirely prevent ridging, for the burning of the copper occurred only under one polarity. It is now considered better practise to stagger the arms in pairs.

With commutating pole machines, the true current densities in the brushes are carried up to as high a point as the non-burning requirements will permit. Reduction in local currents has been accompanied by increase in the work current density. Therefore, conditions for burning and high mica are still existent, as in non-commutating pole machines. In recent years, a new practise, or rather an extension of an old practise, has been very generally adopted, namely, undercutting the mica between bars. In early times, such undercutting was practised to a certain extent, usually however, to overcome mica troubles principally. In the newer practise, such undercutting is primarily for other reasons, although the mica problem is partly concerned in it. During the last few years, extended experience has shown that graphite brushes, or carbon brushes with

considerable graphite in them, are extremely good for collecting current, but on the other hand, are very poor when it comes to wearing down the mica, due to their softness or lack of abrasive qualities Due to the graphite constituent, such brushes are largely self-lubricating, and therefore, "ride" more smoothly on the commutator than the ordinary carbon brush. They are therefore much quieter, and this is a very important point with the present high speeds which are becoming very much the practise. However, by undercutting the mica, all difficulty from lack of abrasive qualities in the brush is overcome, and thus the good qualities of such brushes could be utilized. The advantage of self-lubricating brushes should be apparent to anyone who has had difficulties from chattering and vibration of brushes, due to lack of lubrication. Such chattering may put a commutator " to the bad " in a short time, and the conditions become cumulatively worse. Chattering means bad contact between the brush and commutator, which in turn, means sparking and burning, which means increased chattering or vibration.

The above refers to burning of the commutator face. But such burning also may have a bad effect on the brushes. When the commutator copper burns away to any extent, it may deposit on the brush face following the direction of the current. This coating on the brush face sometimes leads to serious trouble, by lowering the resistance of the contact surface. This not only allows larger short circuit current and greater heating of the brush, but it makes the resistance of that particular path lower than that of other parallel brush paths. In consequence, the coated brush takes an undue share of the total current, as well as an unduly large local current. The resultant heating may be such that the brush actually becomes red hot or glows. This heating further reduces the resistance, and tends to maintain the high temperatures. This glowing or overheating very frequently causes disintegration of the binding or other material in the brush, so that it gradually honeycombs at or near its tip. This action may keep up until the brush makes bad contact. It may be that a similar action may occur coincidently on other brushes, but, there is no uniformity about it. This action of transferring copper to the brush is sometimes known as " picking up copper." It is not limited to brushes of one polarity, except where the metallic coating is caused primarily by the work current. Where it results from

high local currents, it may be on the brushes of either polarity, for the local currents go in and out at each brush. However, according to the writer's experience, this coating is more common on the one polarity

Glowing and honeycombing of brushes is not necessarily dependent upon the metallic coating on the brushes, although this latter increases the action Anything that will unduly increase the amount of current in any brush contact for a period long enough to result in heating and lower contact resistance, with brushes in parallel, may start this glowing and honeycombing. It is not as common an action in modern machines as in old time ones.

As an evidence that poor contact or high contact drop tends to produce burning, may be cited the fact that, in many cases of apparent rapid wear of the commutators, such wear has been practically overcome by simply undercutting the mica and thus allowing more intimate contact between brush and copper. In some instances, this also lessened or eliminated the tendency to pick up copper. Thus undercutting has been very beneficial in quite a number of ways.

NUMBER OF SLOTS, CONDUCTORS PER SLOT, ETC.

There are certain limitations in direct-current machines, depending upon the minimum number of slots per pole which can be used. Provided satisfactory commutating conditions can be obtained, it is in the direction of economy of design to use a relatively low number of slots per pole, with a correspondingly large number of coils per slot. This is effective in several ways. In the first place, insulating space is saved, thus allowing an increase in copper or iron sections, either of which allows greater output. In the second place, wider slots are favorable to commutation. Thus the natural tendency of d-c. design is toward a minimum number of slots per pole. But if this is carried too far, certain objections or disadvantages arise or become more prominent, so that at some point they overbalance the advantageous features. As the slots are widened and the number of teeth diminished, variations in the reluctance of the air gap under the main poles, with corresponding pulsations in the main field flux become more and more pronounced. These may effect commutation, as the short circuited armature coils form secondary circuits in the path of these pulsations But before this condition becomes objec-

tionable, other troubles are liable to become prominent, such as " magnetic noises," etc. If the machine is of the commutating pole type, there are liable to be variations in the commutating pole air gap reluctance, so that it may be difficult to obtain proper conditions for commutation. A relatively wide commutating zone is required if there are many coils per slot; also, all the conductors per slot usually will not commutate under equal conditions, which may result in blackening or spotting of individual commutator bars symmetrically spaced around the commutator, corresponding to the number of slots. In non-commutating pole machines, it may be difficult to find a suitable field or magnetic fringe in which to commutate, and thus the first and last coil in each slot will have quite different fluxes in which to commutate.

Depending upon the relative weight of the various advantages and disadvantages of a small number of slots per pole, practise varies greatly in different apparatus. In small and medium capacity railway motors, where maximum output in minimum space is of first importance, and where noise, vibrations, etc. are not very objectionable, the number of slots per pole used is probably lower than in any other line of d-c. machines, six to eight per pole being rather common. In the smaller and medium size stationary motors, where noise must be avoided, a somewhat larger number of slots is used in general, depending somewhat upon the size of the machine. On still larger apparatus, excepting possibly, small low-speed engine type generators, 10 slots or more per pole are used in most cases, and, in general, more than 12 are preferred. In the large 600-volt machines, the number is fixed partly by the minimum number of commutator bars per pole, and the number of coils per slot. Assuming three coils per slot, then with a minimum number of commutator bars of about 40 per pole, the minimum number of slots per pole will be 14, and with two bars per slot, will be correspondingly larger. This therefore represents one of the limits in present practise.

Noise, Vibration, etc. Mention has been made of limitations of noise and vibration being reached, in considering the minimum number of slots. This is a very positive limitation in design, especially so in recent years, when everything is being carried as close as possible to all limits in economies in materials and constructions. All the various conditions which cause undue noises in electrical apparatus are not yet well known,

and the application of remedies is more or less a question of "cut-and-try."

A fundamental cause of noise in direct-current machines lies in very rapid pulsations or fluctuations in magnetic conditions. This has been well known for years, and many solutions of the problem of preventing such variations in magnetic conditions from setting up vibrations and consequent noise, have been proposed, but many of them appear to hold only for the particular machine, or line of machines, for which they were devised. A perfectly good remedy in one machine not infrequently proves an utter failure on the next one. There are certain remedies for noise in direct-current machines which apply pretty generally to all machines, but, as a rule, such remedies mean more expensive constructions In general, large air gaps and gradual tapering of the flux at the pole edges tend toward quiet operation. A large number of slots per pole tends toward quietness. However, the trend of design has been toward very small air gaps, especially in recent designs of small and moderate size d-c motors, also, the aim has been to use as few armature slots as possible Moreover, newer designs with steel or wrought iron frames, as a rule, have the magnetic material in the frames reduced to the lowest limit that magnetic conditions will permit. Also, with the general use of commutating poles, the tendency has been toward "strong" armatures and correspondingly weak fields, so that the total field fluxes and field frames are relatively small compared with the practise of a few years ago. With these small frames, resonant conditions not infrequently are encountered, especially in those machines which are designed to operate over a very wide range in speed. There is liable to be some point in the speed range where the poles or frame, or some other part, is properly tuned to some pulsating torque or "magnetic pull" in the machine. In such case, a very slight disturbance of a periodic nature may act cumulatively to give a very considerable vibration and consequent noise.

The pulsations in magnetic conditions which produce vibration may be due to various causes, but, as a rule, the slotted armature construction is at the bottom of all of them. Open type armature slots usually are much worse than partially closed slots. Such open slots produce "tufting" or "bunching" of the magnetic flux between the field and armature, and it is this bunching of flux which usually, in one form or another.

produces a magnetic pulsation or pull which sets up vibration. This bunching of lines may be such as to set up pulsating magnetic pulls at no-load as well as full load In other cases, the ampere turns in the armature slots tend to exaggerate or accentuate the bunching so that the vibration varies with the load. This bunching of the flux may act in various ways. The total air gap reluctance between the armature and main poles may vary or pulsate, so that the radial magnetic pull between any main pole and the armature will pulsate in value. If the reluctances under all the poles are varying alike, then these pulsating radial pulls will tend to balance each other at all instants. However, if the reluctances under the different poles do not vary simultaneously, then there are liable to be unbalanced radial magnetic pulls of high frequency, depending upon the number of armature teeth, speed of rotation, etc. If this frequency is so nearly in tune with the natural period of vibration of some part of the machine, such as the yoke, poles or pole horns, armature core and shaft, that a resonant condition is approximated, then vibration and noise are almost sure to occur.

Radial unbalanced pulls, as described, are liable to occur when the number of armature teeth is other than a multiple of the number of poles; and the smaller the number of teeth per pole, the larger will be the unbalancing in general As a remedy, it might be suggested that the number of armature slots always be made a multiple of the number of poles However, there are several objections to this One serious objection is that, on small and moderate size d-c machines, the two-circuit type of armature winding is very generally used, and, with this type of winding, the number of armature coils and commutator bars must always be one more or less in number than some multiple of the number of pairs of poles. Mathematically therefore, with a two-circuit winding, the number of slots can never be a multiple of the number of poles unless an unsymmetrical winding is used, that is, one with a "dummy" coil A second objection to using a number of slots which is a multiple of the number of poles, is that there are pulsating magnetic pulls which may be exaggerated by this very construction There are two kinds of magnetic pulls, a radial, which has already been considered, and a circumferential, due to the tendency of the armature core to set itself where it will enclose the maximum amount of field flux. Obviously, if the arrangement of slots is such that when

one pole has a maximum flux into the teeth, another pole has a minimum, then the circumferential puslations in torque will be less than if all poles enclosed the maximum or the minimum flux simultaneously. This latter condition will be produced when the number of armature slots is a multiple of the number of poles. Therefore, in dodging unbalanced radial magnetic pulls by using a number of armature slots which is a multiple of the number of poles, the designer is liable to exaggerate the circumferential variations in torque or pull, so that he is no better off than before. This circumferential pulsating magnetic pull may act in various ways to set up vibration, and if there is any resonant condition in the machine, vibration and noise will result.

Several years ago, the writer made some very interesting tests on a number of d-c. machines to discover the nature of the vibrations which were producing noise. These machines had very light frames and were noisy, although not excessively so. The following results were noted: In certain four-pole machines, it was noted that the frames vibrated in a radial direction, as could be easily determined by feeling. However, upon tracing around the frame circumferentially, nodal points were noted. In some cases, there were points of practically no vibration midway between the poles, as at A in Fig. 4. In other cases the point of least vibration was at B, directly over the main poles. Apparently, minimum vibration at A and maximum at B occurred when the pulsating magnetic pulls were in a radial direction, while, with circumferential pulls, the maximum vibration was at A. It was also noted in some instances that a variation in the width of the contact face of the pole against the yoke produced vibrations and noise, and nodal points in the yoke, the vibrations being a maximum at A.

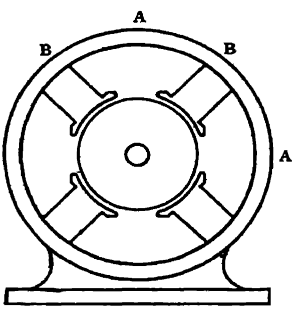


FIG. 4

In still other cases in commutating pole machines, vibrations and noise were apparently set up by either radial or circumferential magnetic pulsations under the commutating poles themselves, as indicated by the fact that removal of the commutating poles, or a considerable increase in their air gaps, tended to overcome the noise. In such cases, the noise usually increased with the load, in constant speed machines.

Skewing of the armature slots, or of the pole faces, has proven quite effective in some cases of vibration and noise. Tapered air gaps at the pole edges have also proven effective in many individual cases However, the causes of the trouble and the remedies to be applied in specific cases are so numerous and so varied that at present it is useless to attempt to give any limitations in design as fixed by noise and vibration due to magnetic conditions.

"FLICKERING" OF VOLTAGE, AND "WINKING" OF LIGHTS

From time to time, cases have come up where noticeable "winking" of incandescent lights occur, this being either of a periodic or non-periodic character, the two actions being due to quite different causes In either case, the primary cause of the difficulty may be in the generator itself, or it may be in the prime mover. The characteristics of the incandescent lamp itself tends, in some cases, to exaggerate this winking To be observable when periodic, the period must be rather long, corresponding to a very low frequency Periodic flickering of voltage may be considered as equivalent to a constant d-c voltage with a low-frequency small-amplitude alternating e m f. superimposed upon it In view of the fact that incandescent lamps of practically all kinds give satisfactory service without flicker at 40 cycles with the impressed e m f varying from zero to 40 per cent above the effective value, one would think that a relatively small variation of voltage, of 3 per cent or 4 per cent for instance, would not be noticeable at frequencies of 5 to 10 cycles per second. However, careful tests have shown that commercial incandescent lamps do show pronounced flicker at much lower percentage variations in voltage, depending upon the thermal capacity of the lamp filament. Based on such thermal capacity, low candle power 110-volt lamps, for example, should show more flicker than high candle power lamps. Also, tungsten lamps for same candle power should be more sensitive than carbon lamps, due to their less massive films. In fact, trouble from winking of lights has become much more pronounced since the general introduction of the lower-candle power, higher-efficiency incandescent lamps.

In view of the fact that winking has been encountered with machines in which no pronounced pulsations in voltage appear to be possible, a series of tests was made some years ago to determine what periodic variation was noticeable on ordinary

low-candle power Tungsten and carbon lamps A lamp circuit was connected across a source of constant direct e m f, and in series with this circuit was placed a small resistance which could be varied at different rates and over varying range The results were rather surprising in the very low pulsations in voltage which showed flickering of the light when reflected from a white surface With the ordinary frequencies corresponding to small engine type generators—that is, from 5 to 10 cycles—periodic variations in voltage of ½ per cent above or below the mean value were sufficient to produce a visible wink, with 16-candle power carbon lamps; while 1 per cent variation above and below was quite pronounced With corresponding tungsten lamps, only about half this variation is sufficient to produce a similar wink. These tests were continued sufficiently to show that such periodic fluctuations in voltage must be limited to extremely small and unsuspected limits This condition therefore imposes upon the designer of such apparatus a degree of refinement in his designs which is almost a limitation in some cases.

It is probable that non-periodic fluctuations in voltage do not have as pronounced an effect in regard to winking of lights as is the case with periodic fluctuations, if they do not follow each other at too frequent intervals, unless each individual pulsation is of greater amplitude, or is of longer duration Possibly a momentary variation in voltage of several per cent will not be noted, except by the trained observer, unless such variation has an appreciable duration

A brief discussion of the two classes of voltage variations may be of interest, and is given below.

Periodic Fluctuations. As stated before, these may be due to conditions inside the machine itself, or may be caused by speed conditions in the prime mover. Not infrequently, the two act together. Variations in prime mover speed can act in two ways; first, by varying the voltage directly in proportion to the speed, and second, by varying the voltage indirectly through the excitation, the action being more or less cumulative in some cases. Such speed variations usually set up pulsations corresponding directly to the revolutions per minute and independent of the number of poles on the machines.

In the machine itself, periodic pulsations of frequency lower than normal frequency of the machine itself, may be caused by magnetic dissymmetry of some sort, or by unsymmetrical windings. Usually, such dissymmetries give voltage fluctua-

tions at a frequency corresponding to the normal frequency of the machine, and therefore will have no visible effect unless such normal frequency is comparatively low, which is usually the case in engine type d-c. generators. In other cases, these dissymmetries may give pulsations corresponding to the revolutions, and not the poles For instance, if the armature periphery and the field bore are both eccentric to the shaft, then magnetic conditions are presented which vary directly with the revolutions.

However, there have been cases where no dissymmetry could be found, and yet which produced enough variations to wink the lights Usually in such cases, the number of armature slots per pole was comparatively small, and the trouble was overcome by materially increasing the number of slots per pole. A second source of winking has been encountered in some three-wire machines in which the neutral tap is not a true central point In such case, the neutral travels in a circle around the central point and impresses upon the d-c voltage a pulsation corresponding to the diameter of the circle Its frequency however, is that of the machine itself and is therefore more noticeable on low frequency machines, such as engine type generators.

Non-Periodic Pulsations or Voltage "Dips." In all d-c. generators, there is a momentary drop or "dip" in voltage with sudden applications of load, the degree of drop depending upon the character and amount of load, etc The effects of this have been noted most frequently in connection with electric elevator operation, in which the action is liable to be repeated with sufficient frequency to cause complaint. Various claims have been made that certain types of machines did not have such voltage dips, and that others were subject to it In consequence, the writer and his associates made various tests in order to verify an analysis of this action which is given below.

The explanation of this dip in voltage is as follows. Assume, for instance, a 100-volt generator supplying a load of 100 amperes—that is, with one ohm resistance in circuit. The drop across the resistance is, of course, 100 volts. Now, assume that a resistance of one ohm is thrown in parallel across the circuit. The resultant resistance in circuit is then one-half ohm However, at the *first instant* of closing the circuit through the second resistance, the total current in the circuit is only 100 amperes, and therefore the line voltage at the first instant momentarily must drop to 50 volts. However, the e.m.f.

generated in the machine is 100 volts, and the discrepancy of 50 volts between the generated and the line volts results in a very rapid rise in the generator current to 200 amperes. If the current rise could be instantaneous, the voltage dip would be represented diagrammatically by a line only, that is, no time element would be involved. However, *the current cannot rise instantaneously in any machine*, due to its self-induction, and therefore, the voltage dip is not of zero duration, but has a more or less time interval. The current rises according to an exponential law, which could be calculated for any given machine if all the necessary constants were known. However, such a great number of conditions enter into this that is it usually impracticable to predetermine the rate of current rise in designing a machine, and it would not change the fundamental conditions if the rate could be predetermined, as will be shown later.

A rough check on the above theory could be obtained in the following manner, by means of oscillograph tests. For example, it was assumed in the above illustration that with one ohm resistance in circuit, an equal resistance was thrown in parallel, which dropped the voltage to one-half. In practise, the actual drop which can be measured might not be as low as one-half voltage, as the first increase in current might be so rapid as to prevent the full theoretical dip from being obtained. However, an oscillograph would show a certain amount of voltage drop. If now, after the current has risen to 200 amperes and the conditions become stable, the second resistance of one ohm is thrown in parallel with the other two resistances of one ohm each, then in this latter case, the resultant resistance is reduced to two-thirds the preceding value, instead of one-half, as was the case in the former instance. Therefore, the dip would be less than in the former case. Again, if one ohm resistance is thrown in parallel with three resistances of one ohm each, the resultant resistance becomes three-fourths of the preceding value,—that is, the voltage dip is still less. Therefore, according to the above analysis, if a given load is thrown on a machine, the dips will be relatively less the higher the load the machine is carrying. Also, if the *same percentage* of load is thrown on each time, then the dips should be practically the same, regardless of the load the machine is already carrying. For example, if the machine is carrying 100 amperes, and 100 amperes additional is thrown on, the dip should be the same as

if the machine were carrying 300 amperes and 300 amperes additional were thrown on.

Also, according to the above theory, a fully compensated field machine, (that is, one with a distributed winding in the pole faces proportioned to correctly neutralize the armature magnetomotive force) should also show voltage dips with load thrown on. To determine if this is so, several series of tests were made on a carefully proportioned compensated field machine. Two series of tests were made primarily. In the first, *equal increments of currents* were thrown on, (1) at half load, (2) at full load, and (3) at $1\frac{1}{2}$ load on the armature. In the second series of tests, a *constant percentage* of load was thrown on; that is, at half load the same current was thrown on as in the first test, while at full load, twice this current, and at $1\frac{1}{2}$ load, three times this current was thrown on.

According to the above theory, all these should show voltage dips, although the machine was very completely compensated. Also, in the first series of tests, the dips should be smaller with the heavier loads on the machine, while in the second series they should be the same in all tests. This is what the tests indicated. In the first series, the dips in voltage varied, while in the second series, they were practically constant. The results of these tests are shown in the following table. (The oscillograph prints were so faint that it was not considered practicable to produce them in this paper.)

NORMAL E.M F—1200 VOLTS.

Test.	Load on generator	Increase in load.	Dip in voltage (Approx).
A	0 Amps	417 Amps	700 Volts
B	208 "	80 "	300 "
C	417 "	80 "	200 "
D	625 "	80 "	150 "
E	417 "	160 "	300 "
F	625 "	240 "	300 "

Tests, B C and D in the table show the dips for the first series of tests, while B, E and F show results for second series. The time for recovery to practically normal voltage was very short in all cases, varying from 0.002 to 0.004 seconds according to the oscillograph curves, but even with this extremely

short time, there was very noticeable winking of tungsten lamps, in practically all tests The oscillograph curves showed practically no change in field current, except in test A.

The machine used in these tests was a special one in some ways. It was a 500-kw., 1200-volt, railway generator with compensating windings and commutating poles. In order to keep the peripheral speed of the commutator within approved practise, it was necessary in the design to reduce the number of commutator bars per pole, and consequently the number of armature ampere turns, to the lowest practical limit. This resulted in an armature of very low self induction, which was very quick in building up the armature current with increase in load. This machine therefore did not show quite as severe variations as would be expected from a normal low-voltage machine of this same construction. However, these two series of tests did show pronounced voltage dips which were sufficient to *produce noticeable winking* of incandescent lamps. Presumably, therefore, all normal types of generators will wink the lights under similar conditions.

Data obtained on non-compensated machines of 125 and 250 volts indicate the same character of voltage dips as were found in the above tests. This should be the case, for, by the foregoing explanation, the compensating winding has no direct relation to the cause of the dip.

It will be noted in these curves that the voltage recovers to normal value very quickly. However, incandescent lamps will wink, even with this quick recovery, if the dip is great enough. There is some critical condition of voltage dip in each machine which would produce visible winking of lights. Any increments of load up to this critical point will apparently allow satisfactory operation. If larger loads are to be thrown on, then these should be made up of smaller increments, each below the critical value, which may follow each other in fairly rapid succession. In other words, the rate of application of the load is of great importance, if winking of lights is to be avoided Therefore, the type of control for motor loads, for instance, should be given careful consideration in those cases where steadiness of the light is of first importance, and where motors and lights are on the same circuit.

An extended series of tests has shown that, in most cases, 10 per cent to 15 per cent of the rated capacity of the generator can be thrown on in a single step without materially affecting

the lighting on the same circuit, and provided the prime mover holds sufficiently constant speed. However, judging from the quickness of the voltage recovery, the prime mover, if equipped with any reasonable flywheel capacity, cannot drop off materially during the period of the voltage dip as shown in the curves. The dip in voltage due to the flywheel is thus apparently something distinct from the voltage dip due to the load. However, if the load is thrown on in successive increments at a very rapid rate, the result will be a dip in voltage due to the prime mover regulation, although the voltage dips due to the load itself may not be noticeable.

The above gives a rough outline of this interesting but little understood subject of voltage variations. Going a step farther, a similar explanation could be given for voltage rises when the load is suddenly interrupted, in whole or in part. This is usually known as the inductive kick of the armature when the circuit is opened This may give rise to momentarily increased voltages which tend to produce flashing, as has already been referred to under the subject of flashing when the circuit breaker is opened.

PERIPHERAL SPEED OF COMMUTATOR

This presents two separate limitations in d-c. design, one being largely mechanical and the other being related to voltage conditions. As regards operation, the higher the commutator speed, as a rule, the more difficult it is to maintain good contact between brushes and commutator face. This is not merely a function of speed, but rather of commutator diameter and speed together. Apparently it is easier to maintain good brush contact at 5000 ft per minute with a commutator 50 in. in diameter than with one of 10 in. in diameter. Very slight unevenness of the commutator surface will make the brushes "jump" at high peripheral speeds, and the larger the diameter of the commutator with a given peripheral speed, the less this is.

The peripheral speed of the commutators is also limited by constructive conditions. With the usual V-supported commutators, the longer the commutator, the more difficult it is to keep true, especially at very high speeds and the higher temperatures which are liable to accompany such speeds. Therefore, the allowable peripheral speeds are, to some extent, dependent upon the current capacity per brush arm, for the length of the commutator is dependent upon this. The per-

missible speed limits, as fixed by mechanical constructions, have been rising gradually as such constructions are improved. At the present time, peripheral speeds of about 4500 ft. per minute are not uncommon with commutators carrying 800 to 1000 amperes per brush arm. In the case of 60-cycle, 600-volt synchronous converters, 5200- to 5500-ft. speeds are usual with currents sometimes as high as 500 to 600 amperes per arm. In the case of certain special 750-volt, 60-cycle converters, operated two in series, commutator speeds of about 6400 ft. have proved satisfactory. These latter, however, had comparatively short commutators.

For the small diameter commutators used in d-c. turbo-generator work, peripheral speeds of 5500 to 6000 ft. have been common. However, such machines usually have very long commutators and of the so-called " shrink-ring " construction. The brushes may not maintain good contact with the commutator at all times, and in a number of machines in actual service, the writer, in looking at the brush operation, could distinctly see objects beyond the brush contacts; that is, one could see " through " the contact, and curiously, in some of these cases, the machines seemed to have operated fairly well. One explanation of this is that the gaps between brushes and commutator were intermittent, and, with one or more brush arms in parallel, one arm would be making good contact, while another showed a gap between brushes and commutator. Apparently, the commutators were not rough or irregular, but were simply eccentric when running at full speed and the brushes could not rise and fall rapidly enough to follow the commutator face all the time. Incidentally, it may be mentioned at this point, that with the higher commutator speeds now in use, there has come the practise of " truing " commutators *at full speed.* This is one of the improvements which has allowed higher commutator speeds.

The other limitation fixed by peripheral speed, namely, that of the voltage, is a more or less indirect one. It is dependent upon the number of commutator bars that are practicable between two adjacent neutral points; or, in other words, it is dependent upon the distance between neutral points. The product of the distance between adjacent neutral points and the frequency, in alternations, gives the peripheral speed of the commutator, (distance between neutral points in feet times alternations per minute equals peripheral speed in feet per

minute). With a given number of poles and revolutions per minute, the alternations are fixed Then, with an assumed limiting speed of commutator, the distance between neutral points is thus fixed. This then limits the maximum number of commutator bars, and therefore the maximum voltage which is possible, assuming a safe limiting voltage per bar From this it may be seen that the higher the peripheral speed, the higher the permissible voltage with a given frequency In the same way, if the frequency can be lowered (either the speed or the number of poles be reduced) the permissible voltage can be increased with a given peripheral speed. Where the speed and the number of poles are definitely fixed and the diameter of commutator is limited by peripheral speed and other conditions, the maximum practicable d-c voltage is thus very definitely fixed. This is a point which apparently has been misunderstood frequently It explains why, in railway motors, for high voltages, it is usual practise to connect two armatures permanently in series, also, why two 60-cycle synchronous converters are connected in series for 1200- or 1500-volt service. In synchronous converter work, the frequency being fixed once for all, the maximum d-c. voltage is directly dependent upon the peripheral speed of the commutator

Conclusion

The principal intent, in this paper has been to show that certain limitations encountered in d-c. practise are just what should be expected from the known properties of materials and electric circuits. The writer has endeavored to explain, in a simple, non-mathematical manner, how some of the apparently complicated actions which take place in commutating machinery are really very similar to better understood actions found in various other apparatus An endeavor has also been made to show that a number of the present limitations in direct current design and operation are not based merely upon lack of experience, but are really dependent upon pretty definite conditions, such as the characteristics of carbon brushes and brush contacts, etc Possibly a better understanding of the characteristics and functions of carbon brushes will result from this paper.

The writer makes no claims to priority for many of the ideas and suggestions brought out in this paper However, much of the material is a direct result of his own investigations and those of his associates during many years of experience with direct-current apparatus

APPENDIX

The following method of determining the maximum capacity which can be obtained with given dimensions and for assumed limitations as fixed by commutation, flashing and other conditions, is based upon certain formulas which the writer developed several years ago, and which appeared in a paper before the Institute.*

On page 2389 of the 1911 TRANSACTIONS of the Institute, the following general equation is given:

$$E_c = \frac{I_c\,W_t\,R_s\,T_c\,\pi}{10^8}\left[c_1\,(L - L_1)\,\frac{2\,Dp}{(0\,25\,p + 0\,5)\ (D + P_p)} + c_2\frac{4\,D}{p}(0\,9 + 0.035\,N) + c_3\,\frac{L}{s}(1.33\,d_s + 0.52 + 2.16\,s\,\sqrt{n})\right] + \frac{c_4 2\phi\ Np\,R_s T_c}{10^8} \qquad (1)$$

Where I_c = Current per armature conductor.
W_t = Total number of armature conductors
T_c = Turns per armature coil or commutator bar.
L & L_1 = Width of armature core and commutating pole faces respectively.
D = Diameter of armature.
p = No. of poles.
N = No. of slots per pole.
d_s = Depth of armature slot.
s = Width of armature slot.
n = Ratio of width of armature tooth to slot at surface of core.
c_1, c_2, c_3, c_4 are design constants.

In order to simplify the above equation, the following assumptions are made:

(a) No bands are used on armature core, thus eliminating the last term in the above equation.

(b) $L_1 = L$, thus eliminating the first expression inside the bracket in the above equation.

Both the above assumptions are in the direction of increased capacity with a given short circuit voltage, E_c.

Equation (1) then becomes,

*Theory of Commutating and Its Application to Commutating-Pole Machines, Page 201.

$$E_c = \frac{I_c W_t R_s T_c \pi}{10^8}\left[c_2 \frac{4D}{p}(0.9 + 0.035N)\right.$$

$$\left. + c_3 \frac{L}{s}(1.33d_s + 0.52 + 2.16\, s\sqrt{n})\right] \qquad (2)$$

The various terms in equation (2) should be put in such form that limiting values can be assigned to them as far as possible. In order to do this the equation can be condensed and simplified as follows, for large machines:

(a) Assuming parallel type windings,—

$W_t = \dfrac{T_c 2p\,E}{V_b}$, where V_b = Average volts per commutator bar or coil.

$I_c = \dfrac{I_t}{p}$ where I_t = Total current.

IE = Kilowatts $\times 10^3 = Kw\,10^3$

Also, $R_s\,p = 2f$, where f = Frequency in cycles per second.

Therefore, $\dfrac{I_c W_t R_s T_c \pi}{10^8} = \dfrac{Kw_p \times 4f\,T_c^2\pi}{V_b \times 10^5}$, Kw_p being the kilowatts per pole.

(b) Let P_t = Armature tooth pitch.

$$\text{Then } D = \frac{Np\,P_t}{\pi}$$

$$\text{and } c_2 \frac{4D}{p}(0.9 + 0.035\,N) = c_2 \frac{4N}{\pi}(0.9 + .035\,N)\,P_t$$

In case of a chorded winding, the term 0.035 N should be 0.035 N_1, where N_1 represents the number of teeth or tooth pitches spanned by the coil.

(c) In the second term inside the bracket in equation (2), the ratio $\dfrac{L}{S}$ can be transformed into an expression containing P_t, as follows:

$$E = \frac{B_t S_t C_p R_s W_s}{10^8}$$

B_t = Flux density in armature teeth.
S_t = Section of iron in armature teeth.
C_p = Field form constant (percentage polar area).
R_s = Revolutions per second.
W_s = Wires in series.
S_t = $N\,T\,p\,L\,c_5$, where T = Width of tooth, and c_5 = the ratio of actual iron to the core width L.

As an approximation, $T_{xs} = \dfrac{P_t^2}{4}$ (This is a fairly close approximation within practical limits in the usual armature constructions).

$$\text{Then, } S_t = N\,p\,c_5\,\frac{P_t^2}{4}\left(\frac{L}{s}\right)$$

$$\text{and } E = \frac{B_t\,C_p\,R_s\,W_s\,N\,p\,c_5\,P_t^2}{4 \times 10^8}\left(\frac{L}{s}\right)$$

$$\text{or} \qquad \frac{L}{S} = \frac{4 \times 10^8\,E}{B_t\,C_p\,R_s\,W_s\,N\,p\,c_5\,P_t^2}$$

This can further be condensed as follows.

$$W_s = T_c\,\frac{2E}{V_b},\ \text{and } R_s\,p = 2\,f$$

$$\text{Therefore, } \frac{L}{s} = \frac{10^8\,V_b}{B_t\,C_p\,N\,f\,c_5\,P_t^2 T_c}$$

(d) The expression $(1.33\ d_s + 0.52 + 2.16\,s\sqrt{n})$ can be modified as follows,

$$\sqrt{n} = \sqrt{\frac{T}{s}} = \sqrt{\frac{P_t^2}{4s^2}} = \frac{P_t}{2s} \text{ on the basis that } T_{xs} = \frac{P_t^2}{4}$$

approx.

Then, $2.16\,s\sqrt{n} = 1.08\,P_t$ approx.

and, $(1.33\,d_s + 0.52 + 2.16\,s\sqrt{n}) = (1\,33\,d_s + 0.52 + 1.08\,P_t)$

Substituting all the above transformations in equation (2) we get,

$$E_c = \frac{K w_p\,f\,T_c^2\,4}{V_b \times 10^5}\Bigg[c_2 4\ (0.9 + 0\,035\,N_1)\,N\,P_t$$

$$+ \frac{\pi\,c_3\,V_b\,10^8}{B_t\,C_p\,N\,f\,c_5\,P_t^2\,T_c}\,(1.33 d_s + 0.52 + 1.08\,P_t)\Bigg] \qquad (3)$$

$$Kw_p = \frac{E_c V_b 10^5}{4 T_c^2}$$

$$\frac{P_t^2}{\left[4c_2 (0.9 + 0\ 035 N_1) N f P_t^3 + \frac{\pi c_3 V_b 10^8}{B_t C_p N c_5 T_c} (1\ 33 d_s + 0.52 + 1\ 08 P_t\right]} \quad (4)$$

Maximum Kilowatts per Pole. Differentiating (**4**) to obtain P_t for maximum Kw_p,

$$P_t^3\, 4 c_2 N f (0.9 + 0.035 N_1) = \frac{\pi 2 c_3 V_b 10^8}{T_c B_t C_p N c_5} (1\ 33 d_s + 0\ 52)$$

$$+ \frac{\pi c_3 V_b 10^8}{T_c B_t C_p N c_5} \times 1.08 P_t \qquad (5)$$

If P_t in equation (**5**) could be derived and then substituted in equation (**4**), then for any assumed value of E_c and with the other terms given limiting values, an expression for the maximum kilowatts per pole could be obtained. The writer has not been able to solve this directly in any sufficiently simple manner, although a complicated approximate expression can be obtained. However, for practical purposes, the solution for any given conditions can be obtained by trial methods and the results plotted in curves.

For instance, in equations (**4**) and (**5**), the following terms may be given limiting values for a given class of machines and for a specified voltage

T_c = Turns per coil
c_2 = End flux constant.
N = Number of slots per pole N_1 = No. of teeth spanned by coil.
c_3 = Brush short circuit constant.
V_b = Average volts per bar.
C_p = Field form constant With max. volts per bar fixed, then V max. $\times C_p = V_b$.
B_t = Flux density in teeth.
c_5 = Ratio of actual iron width to core width L.

Also, type of armature winding can be fixed and departure from full pitch winding, or amount of chording can be given.

There will then remain for any assumed value of E_c, the terms,

Kw_p = Kilowatts per pole.
P_t = Tooth pitch.
f = Cycles per second.
d_s = Depth of armature slot.

All four of these latter terms are in equation (**4**), and the last three in equation (**5**). Therefore, assuming the depth of slot, equation (**5**), the values of P_t for different frequencies may be determined by trial methods. The corresponding values of P_t, f and d_s can then be substituted in equation (**4**), and the kilowatts per pole thus determined. Tables or curves can then be prepared giving the kilowatts per pole for different frequencies and for different assumed slot depths.

A series of such tables have been worked out for a specified set of conditions as given below. The assumed limiting conditions were as follows:

E_c = 4.5,—that is, one turn per coil parallel type winding is assumed.

e m f = 600 volts.

C_p = 0.68

V_b = 14.3. No of commutator bars per pole = 42. No compensating winding is used. Therefore, V_b $= \frac{600}{42}$, and max. volts per bar at no load = $\frac{14.3}{0.68} = 21.$ Allowing 25 per cent increase for flux distortion, and increased voltages at times, gives 26 3 at full load.

C_2 = 1.25 for average constructions.

C_3 = Varies with the number of coils per slot and the average number of bars covered by the brush, but assuming 2 bars covered, then C_3 = 0.4 approx. with 1 slot chording, and with either 2 or 3 coils per slot.

B_t = 150,000 lines per sq. in. on the basis of actual iron and all flux confined to the iron.

C_5 = 0.75. This allows for 90 per cent solid iron and $\frac{1}{6}$ of the total width taken up by air ducts (about $\frac{3}{8}''$ duct for each $2''$ of laminations).

$N = 14$
$N = 21$ } Two cases have been assumed, one with 3 coils per slot and 14 slots per pole, and the other with 2 coils per slot and 21 slots per pole.

14 *Slots per Pole.*—Substituting the above values in equations (4) and (5), then for 14 slots per pole equation (4) becomes,

$$Kw_p = 3767\, E_c \left[\frac{P_t^2}{f\, P_t^3 + 9.18\ (2.5\, d_s + 1) + 19\, P_t} \right] \tag{6}$$

and equation (5) becomes

$$f\, P_t^3 = 18\ 36\ (2.5\, d_s + 1) + 19\, P_t \tag{7}$$

Incidentally, equation (6) can be simplified to a certain extent by partially combining with equation (7), giving the following equation:

$$Kw_p = 99\, E_c \left[\frac{P_t^2}{0.725\ (2.5\, d_s + 1) + P_t} \right] \tag{8}$$

Equation (8), of course, can only be used with the values of P_t determined from equation (7).

Three values for d_s were chosen, 1 in., 1.5 in., and 2 in., which cover the practical range of design for large d.-c. generators. Frequencies from 5 to 60 cycles were also chosen. The corresponding values for P_t and Kw_p are tabulated below.

TABLE I.

f— Cycles per sec.	$d_s = 1''$		$d_s = 1\ 5''$		$d_s = 2''$	
	P_t	Kw_p	P_t	Kw_p	P_t	Kw_p
5	2 85 in.	670	3 08 in	647	3 255 in	620
10	2 20	453	2 362	428	2 504	407
20	1 685	299	1 828	282	1 945	266
30	1 455	235	1.575	219	1 680	208
40	1 302	197	1 417	183 5	1 515	173
50	1.20	173 5	1 305	160	1 398	151 5
60	1 125	153	1 226	143 5	1 310	135

21 *Slots Per Pole.* Substituting the proper values in equations (4) and (5) for 21 slots per pole, and one slot chording, and then solving for P_t and Kw_p for the same slot depths and frequencies, the following table is obtained:

TABLE II.

f— Cycles per sec.	d_s = 1 in.		d_s = 1 5 in.		d_s = 2 in	
	P_t	Kw_p	P_t	Kw_p	P_t	Kw_p
5	1 985 in.	576	2 14 in	542	2 27 in	515
10	1 53	380	1 56	335	1 77	338
20	1 185	249	1 29	232	1 36	214
30	1 022	195	1 12	181	1 192	168
40	0 922	163	1 005	150	1 077	141
50	0 850	142	0 932	131	0 997	123
60	0 796	126	0 874	117	0 936	110

Synchronous Converters

Two cases only need be considered, namely 25 and 60 cycles. For these two cases, more definite limits can be given than for the above rather general solution for d-c. machines.

25 *Cycles*. Let $N = 21$, and $N_1 = 20$; also, assume two coils per slot for 600 volt machines.

$c_2 = 1.0.$
$c_3 = 0.37$
$B_t = 165{,}000$
$C_p = 0.7$

Then for assumed values for depth of slot of 1 in., 1.5 in , and 2 in., and for $E_c = 4.5$, the following values of P_t and Kw_p are obtained:

TABLE III.

Depth of slot.	Tooth pitch.	Kilowatts per pole.
1 in	1.09	278
1 5	1 19	257
2	1 275	243

60 *Cycles*. Let $N = 15$, and $N_1 = 14$. Also, assume 3 coils per slot for 600 volts.

$c_2 = 1.0$
$c_3 = 0.4$
$B_t = 150.000$
$C_p = 0.66$

Then assuming slot depth of 1 in., 1.25 in., and 1.5 in., and $E_c = 4.0$, the following values of P_t and Kw_p result:

TABLE IV.

Depth of slot	Tooth pitch.	Kilowatts per pole.
1 in	1.14	143
1.25	1.195	137.5
1.5	1.24	132

The above tabulated results agree pretty well with practical results obtained in large generators and converters. There are so many possible variations in the limits assumed that only general results can be shown. For instance, in Table I, a constant limiting induction in the armature teeth of 150,000 lines per sq. in. is assumed. With low frequencies this can be increased, while with frequencies of 50 to 60 cycles, somewhat lower inductions will be used. Also, the commutation constant C_1 which is dependent upon the number of bars covered by the brush is naturally subject to considerable variation.

The results obtained are predicated upon parallel types of windings and a minimum of one turn per armature coil. If types of windings having the equivalent of a fractional number of turns per coil less than one, prove to be thoroughly satisfactory for large capacity machines, then the above maximum capacities can be materially increased. However, accepting the results as they stand, the limits of capacity as fixed by commutation are in general about as high as other limitations will allow.

REGULATION CHARACTERISTICS OF COMMUTATING POLE MACHINES AND PARALLEL OPERATION WITH OTHER MACHINES

FOREWORD—About ten years ago, the author found that there was considerable misunderstanding regarding the regulating characteristics of commutating-pole machines, and the conditions which were to be met in parallel operation. In consequence, he prepared this brief article for the use of the engineers of the Westinghouse Electric & Manufacturing Company. It has proved so satisfactory that it has been kept in publication ever since.

This paper was written before the term "commutating pole" was adopted to replace the term "interpole" which is found throughout the article.—(ED.)

THE inherent regulation characteristics of the armature of a direct-current machine has much to do with its parallel operation with other machines. When two direct-current armatures are coupled in parallel and delivering load to the same external circuit, it is necessary, in order to obtain stable conditions, for each armature to tend to "shirk" its load; that is, it must naturally tend to transfer load to the other machine. This tendency to shirk may be either in bad speed regulation due to the prime mover which drives the armature, or in the drooping voltage characteristics of the armature itself. A drooping speed characteristic indirectly produces a drooping voltage characteristic in the armature and therefore both causes lead to the one characteristic, namely, drooping voltage, as the condition for stable parallel operation. This drooping voltage characteristic must be the inherent condition. In practice, the voltage at the armature terminals frequently rises with increase in load, but its rise is due to some external condition, such as increased field strength.

Direct-current machines, as hitherto ordinarily constructed, naturally give drooping voltage characteristics in the armature windings. If two such armatures are paralleled they tend to divide the load in a fairly satisfactory manner provided their prime movers regulate similarly in speed. If means are applied for giving a rising voltage characteristic to the machines, such as series coils in the field, then the armature terminals must be paralleled directly in order to maintain stability. If, for instance, the armatures are not paralleled directly, but the paralleling is

done outside the series coils, then the operation will be unstable unless the machines still have drooping voltage characteristics If they have rising characteristics, then parallel operation is impracticable. If either machine should take an excess of load, its voltage would rise, while that of the other machine would fall due to decreased load. This condition would naturally force the first machine to take still more load and the second one to take still less This condition would continue until the first machine actually fed current back through the other machine and it would be necessary to cut them apart to avoid injury. However, by paralleling the two armatures inside the series coils, that is, between the series coils and the armature terminals, this unstable condition is avoided due to two reasons, first, the inherent drooping voltage characteristics of the armatures, and, second, the fact that the series coils are paralleled at both terminals, thus forcing them to take proportional currents at all times and thus compounding both machines equally.

If direct current machines are so designed or operated as to give rising instead of drooping armature characteristics, then parallel operation is liable to be unstable. This condition could be obtained in ordinary machines by prime movers which tend to speed up with increasing load, thus producing rising voltage on the armature. Ordinarily, such speeding up of the prime mover would have to be rather large, as the normal drooping characteristics of the ordinary armature is fairly large. However, prime movers of this character are comparatively rare.

A second condition which can give a rising voltage is found not infrequently in the interpole type of direct-current machine. The interpole generator is similar to the ordinary type of generator, except that midway between the main poles small poles are placed which carry windings or coils which are connected directly in series with the armature. The winding on the interpoles is connected directly in opposition to the winding in the armature. The maximum magnetizing effect of the armature winding is found at the points on the armature corresponding to the coils which are being commutated. The interpole is intended to be placed directly over these points and the interpole winding normally has such a value that it not only neutralizes the magnetizing effect to the armature winding at these points, but it also sets up a small magnetic field in the opposite direction which assists in the commutation of the armature coil. Therefore the interpole winding

must have a number of ampere turns equal to the maximum ampere turns in the armature winding, plus the excess ampere turns necessary to produce the required commutating field strength.

When this interpole winding is placed directly over the commutating position of the armature winding it should have practically no effect on the armature characteristics. If, however, the interpole winding is not placed over these positions it will have an effect on the voltage characteristics of the machine, tending to either raise or lower the voltage, depending upon the position of the interpole with respect to the commutating position. The commutating points on the armature depend directly upon the brush position If the brushes are rocked backward or forward from the point corresponding to the mid position between the poles then the position of the commutated armature coils moves backward or forward with the brushes. As the commutating pole is fixed in position it is evident that the relation of the commutating pole to the coils undergoing commutation can be changed by the different brush settings. Herein lies a possible trouble in parallel running, for the commutating points can be so shifted, with respect to the commutating pole, that the armature winding voltage characteristics can be made to rise instead of droop. As explained before, this is an unstable condition for parallel operation.

This condition can be illustrated in the following manner:

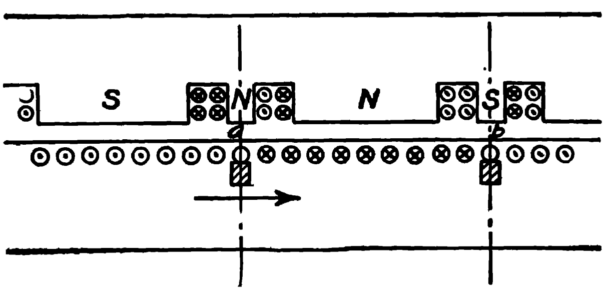


FIG. 1

Let Fig. 1 represent two main poles, and interpoles, with the brushes set in a position corresponding to the middle point of the interpole. The polarity of the interpoles and main poles is indicated in this figure. The polarity of any interpole, when the machine is running as a generator, is always the same as the polarity of the main pole immediately in front of the interpole. When the brush is placed in a position corresponding to an exact intermediate point in the interpole it is evident that the aramture

coils lying between two commutating points, that is, the winding between **a** and **b** in Fig. 1, is acted upon by induction from the main pole and by half the induction from the interpoles adjacent to the main pole. However, as these two interpoles are of opposite polarity, and the induction is the same from each, it is evident that they have equal and opposite effects on the armature winding between **a** and **b**, and therefore do not affect its voltage

In Fig. 2 the brushes are given a slight back lead so that the commutation is under the trailing magnetic flux from the interpole. It is now evident that between **a** and **b** the induction is from the main pole and from one interpole principally. With the back lead at the brushes, this interpole is the one immediately behind the main pole and therefore of the same polarity. This interpole therefore becomes a magnetizing pole and adds to the e. m. f. generated between **a** and **b** As the strength of this interpole is zero at no load and rises with load, it is evident that it tends to give an increased voltage between **a** and **b** as the load increases and thus tends to produce a rising voltage characteristic instead of a drooping one. The ampere turns in the interpole, as stated before is considerably greater than in the armature, but ordinarily the effect of these ampere turns is almost neutralized by the opposing effect of the armature winding However, with the

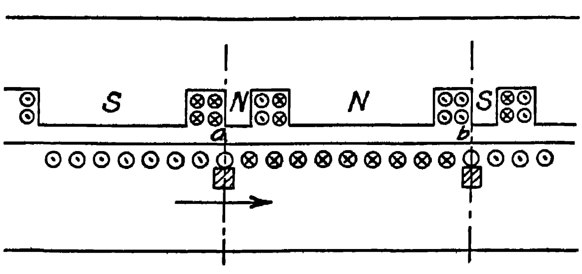


FIG. 2

back lead, as indicated in Fig. 2, the opposing effect of the armature winding is shifted to one side of the interpole and thus the interpole ampere turns become more effective in actually magnetizing the armature, but become less effective in creating a commutating field for the coils which are now being reversed by the brushes. On account of this less effective field it may be necessary in practice to still further increase the ampere turns on the commutating poles in order to bring the trailing magnetic fringe up to a suitable value for producing proper commutation. It is evident that this

increased ampere turns on the commutating pole increases the induction under other parts of the commutating pole as well as under the trailing tip, and this increase under the other parts of the pole still further increases the voltage between **a** and **b**.

With a back lead therefore the interpole may have the same effect as the series winding on the main field; that is, it may compound the machine so that the voltage at the terminals is rising instead of falling, even without any true series winding on the main poles. The machine therefore becomes an equivalent of a compound wound machine and if there is no equalizer between the interpole winding and the armature terminal, the generator may be unstable when paralleled with other machines.

Take the case, next, where the brushes are given a forward lead, as shown in Fig. 3. Comparing this with Fig. 2, by the same reasoning it is evident that the interpole is now opposing the effect of the main pole, in the winding between **a** and **b**. The interpole therefore tends to produce a drooping voltage characteristic and has just the opposite effect of the series winding. In this position of the brushes the interpole winding tends to give good characteristics for parallel operation, but as the effect of the interpole is in opposition to the main pole it is evident that more series winding is required on the main field in order to over-compound the machine as a whole. Also, with the brushes in this position the interpole is not as effective in producing good commutation and therefore more ampere turns are required on their interpole winding. Therefore, both the interpole winding and the main series winding must be increased when the brushes are given this forward postion. However, parallel operation should be stable.

It is evident, therefore, from the above considerations, that for best results the brushes should be so set that the true point of commutation comes midway under the interpole. If this position

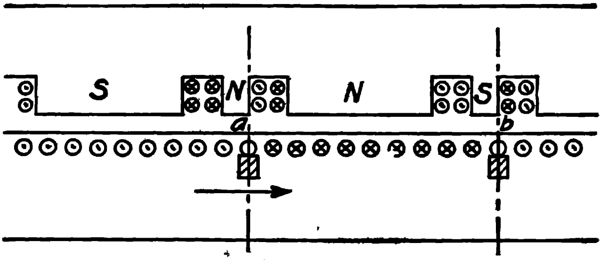


FIG. 3

is found exactly, then the interpole should have practically no effect on the voltage characteristics of the armature, and parallel operation with other generators should be practicable A very slight forward lead is favorable to paralleling, but lessens the compounding.

As a back lead at the brushes, when the machine is acting as a generator, tends to improve the compounding and lessens the series winding required on the main field, it might be suggested that this gives a cheaper and more efficient machine and that therefore this arrangement should be used, with some means added for overcoming the unstable conditions of paralleling. One means proposed for this is an additional equalizer connected between the interpoles and the armature terminals. This has been used in one or two instances, but in principle the arrangement is inherently wrong. When the interpole windings are paralleled, then the currents in them must divide according to their resistances. This condition would not be objectionable provided the armature currents also always varied in the same proportion. With slow changes in load this condition might be obtained. However, there are conditions of operation where the armature currents will not rise and fall in proportion and therefore the interpole windings, with this arrangement, would not always have the right value to produce the desired commutating fields. By rights, each armature should be connected directly in series with its own interpoles and the currents in the two should rise and fall together for best results. This condition will not be obtained when an equalizer is connected between the armatures and interpoles. This solution of the problem should therefore be avoided in general.

All the above leads to the fact that very accurate brush setting is required on interpole types of machines, and furthermore, when such setting is once obtained it should not be capable of ready adjustment or change. For this reason interpole machines should not have any brush rocking gear. In machines where such gear is present it would be better, in general, if the brush rocking mechanism were removed after the proper setting of the brushes is once obtained, and means should be employed for locking the brushes in this correct position.

The correct setting of the brushes is rather difficult to obtain in many cases. Where the armature conductors can be traced from the commutator bars back under the poles, it is feasible in

general to locate the correct setting by the position of the commutated coil with respect to the interpoles. In standard practice the throw or span of the coil is made, as nearly as possible, equal to the pole pitch. In a parallel type of winding where the number of slots is an exact multiple of the number of poles, the space of the coil can be made exactly equal to the pole pitch. In this case if the winding can be traced through, the brushes can be so set that a coil or turn exactly under the middle of the commutating poles has its two ends connected to the two adjacent commutator bars which are symmetrically short-circuited by the brush; that is, the insulating strip between these two bars should be under the middle of the brush. To carry this out properly it is necessary to trace the conductor, with absolute exactness, through the slots When there are several separate turns side by side in one slot, it is advisable to select a middle, or approximately middle, turn for determining the brush setting.

In the case of a 2-circuit or series winding, it is more difficult to determine the brush setting by tracing out the coils, for the number of slots in such windings is usually not an exact multiple of the number of poles and therefore the span of the coil is not exactly equal to the pole pitch. In this case the position of the coil must be averaged; that is, one edge or half of the coil may be slightly ahead of the middle point of its interpole, while the other half is slightly behind the middle of the interpole. Even if the position of the coil is properly fixed it is not easy to fix exactly the corresponding brush setting, as the two commutator bars to which the coil is connected do not lie adjacent to each other, as in a parallel type of winding, but are two neutral points apart. Also, the number of commutator bars is not an exact multiple of the number of poles (except in some rare cases where there is an idle bar) and therefore they do not have a symmetrical relation to the brushes. The best that can be done therefore is to average the brush position as well as possible.

If the winding is chorded; that is, if it has a span considerably shorter than the pole tip, then its position will have to be averaged in the manner described above.

In some cases it is not practicable to trace out the coils in the above manner, as the end windings may be so covered that it is not possible to trace an individual coil from the commutator to the slot.

On later machines it is the practice to put a mark or "cross" on the tops of two adjacent armature teeth The top conductors which lie in the slot between these two teeth are connected to commutator bars which are also marked with a cross at their outer ends. In this way it is possible to trace from the commutator to the slots.

When an interpole generator is running alone, or where it is operating properly with other machines, and the commutation is satisfactory, it is unnecessary, of course, to look into this question of locating the best brush setting. In those cases, however, where the machine does not parallel properly with others, and it is evident that the brush setting is wrong, then if the above procedure cannot be followed, a better brush setting can be found by determining the voltage characteristics of the armature This can be done by operating the machine with various loads with the series winding cut out of circuit. If, under this condition, the voltage either rises with increase in load, or droops but very little, then it is evident that a greater forward lead would improve the operation. The brushes could then be shifted slightly forward and the regulation noted. After a brush setting has been obtained which gives a considerably larger drop in the voltage, then parallel operation should again be tried with this brush setting, the series coils, of course, being connected in circuit. After proper paralleling is obtained, then it may be necessary to re-adjust the strength of the commutating field. If the machine has had a considerable back-lead before and is shifted to the no-lead condition, then it may be necessary to weaken the interpole winding somewhat. If the new brush setting however, should correspond to as much forward lead as it had back lead before, then the interpole strength may not require readjustment and the commutation may be just as good as before. After the proper conditions have been obtained, the brush holder position should be marked so that it can be readily found again if necessary.

There is another feature wherein an interpole machine is different from the non-interpole type, namely, in the amount of series winding. In the non-interpole type the brushes are usually given a very considerable forward lead. In consequence of this forward lead a part of the armature ampere turns are actually effective in demagnetizing the field, and extra series turns are necessary simply to overcome this demagnetizing effect, without accomplishing any useful result.

On the interpole type, however, with the brushes set properly there is no lead at the brushes and therefore none of the armature turns are tending to directly oppose the main field. In consequence of this the number of series turns may be reduced and the resistance of the series coils is correspondingly reduced. When operating interpole machines in parallel with other types it may be necessary to increase the resistance of the series circuit in order that the interpole machine may take its proper share of the current through the series coils. This result is obtained best, in general, by a resistance connected in series with the series coil and not by a shunt connected across the series coils of the other machines. A shunt across a series coil of one machine is, in reality, a shunt across all the machines which are operating in parallel, and it may be more effective, in one machine simply because of the resistance of the leads connecting the various machines. These statements apply to other types of machines as well as the interpole.

HIGH SPEED TURBO-ALTERNATORS—DESIGNS AND LIMITATIONS

FOREWORD—This paper was prepared for the American Institute of Electrical Engineers at the request of the Power Station Committee of the Institute. It was presented in January, 1913 It contains a quite complete description of the two principal types of turbo alternator rotors up to that time. In the latter part of the paper, it takes up the problems of ventilation, temperature and insulation from the turbo-generator standpoint. Attention was called to the high temperature liable to be encountered in very wide core machines, such as turbo-generators, due, to a certain extent, to mechanical limitations. The necessity for the use of mica in such windings was also brought out.—(ED.)

THE real problems in the design of turbo-alternators did not really develop until the high-speed, large capacity units came into demand. In the earlier work, the difficulties in design were mostly those due to lack of experience and to insufficient knowledge of the possibilities of materials, etc. As more data were obtained, the speeds and capacities were gradually increased until with the present large capacities and high speeds, a number of conditions are encountered which may be considered as true physical limitations.

The principal difficulties in the design of the earlier machines were found in the permissible weight on bearings, undue noise due to the open construction of the machines, and the troubles incident to the through-shaft construction of the rotor.

The bearing problem was eliminated by securing more complete data, which showed that the possibilities in this feature had hardly been touched upon.

The solution of the noise problem was largely one of enclosing the machine. The noise was practically eliminated, but the greater problem of ventilation then developed.

In overcoming the difficulties of the through-shaft construction, the first great advance was made in the direction of larger outputs at higher speeds. In very high-speed machines, the diameter of the shaft in the rotor core is necessarily small. As the overall diameter of the core is comparatively small, it follows that, after allowing for the slot depth, and the metal in the

core necessary to withstand the high rotative stresses, there is left but little available space for the shaft. About 600 kv-a. capacity at 3600 rev. per min. was the limit with this construction.

The first great advance in this problem was made by the introduction of rotors without the through-shaft. By this means, the parts of the shaft adjacent to the rotor core proper, could be very much heavier than with the through-shaft type, and this combined, with the solid rotor core, gave great stiffness or rigidity compared with the former through-shaft type. This allowed much larger cores, with correspondingly increased outputs. The two-pole parallel slot type of rotor with bolted-on shaft construction, as described later, was apparently a leader in this respect, due to mechanical, rather than electrical, characteristics. When this type had proved to be a successful one, the possible capacities of two-pole 3600-revolution, 60-cycle machines at once jumped from 600 to 1000 kv-a., and this was

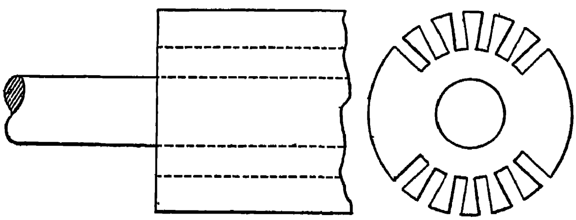


Fig. 1

quickly followed by 1500, 2000 and 3000 kv-a. units at 3600 revolutions. Since then, the increase in capacity at this speed has been more gradual, but has been carried up to 5000 kv-a. at present, with possibilities of a 6250 kv-a. unit.

The radial slot type of rotor, also described later, when constructed with its core and shaft in one piece, quickly followed the parallel-slot type in the above growth, and may eventually catch up with its only rival in the two-pole, 60-cycle field of construction.

About the same time that the through-shaft type was superseded in the two-pole, 60-cycle machine, a corresponding change was made in the two-pole, 25-cycle, and in four-pole rotors for both frequencies, so that, at the present time, practically no designs for the highest speed machines use the through-shaft type of construction. This latter, however, has been retained in some of the more moderate speed large capacity units.

On account of the high rotative and peripheral speeds, the general design of large capacity turbo-generators turns upon the type and construction of the rotor, rather than the stator. Various designs and types of rotors have been developed but, with rare exceptions, only two general types are now built in this country. These may be designated as the radial-slot and the parallel-slot types. Each has a number of advantages over its rival and each has given good results in practice.

Radial Slot Type of Rotor

In the radial slot type, as usually constructed for high-speed machines, the core and shaft are forged in one piece in the smaller and more moderate sizes, but may be built up of a number of separate plates or disks bolted rigidly together in the larger sizes. In this type, the core is cylindrical in all cases, and in the outside surfaces are radial slots, usually arranged in groups, in which the

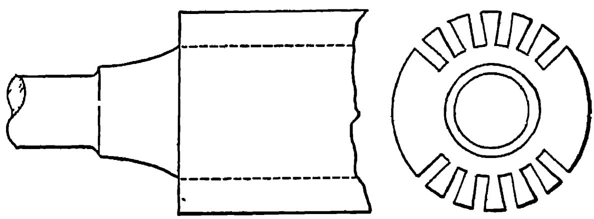


Fig. 2

exciting windings are placed. While all radial slot types of rotors bear a general resemblance to each other, yet there are marked differences in the method of forming the slots and teeth which constitute the outer surface. In some types the solid rotor core has radial slots milled or slotted in the main body of the core. In other cases the slots are formed outside the main core by inserted teeth, usually with overhanging tips, between which the exciting coils lie. These two general constructions are illustrated in Fig. 3. Examples of the inserted-tooth construction are found in the large moderate speed rotors of one American company, and in somewhat higher speed machines of a German company. However, with the advent of the high-speed, high-capacity machines, the milled-in construction of the radial slots appears to be taking the lead, due to certain mechanical limitations in the inserted-tooth types.

On account of the radial slots and the usual concentric arrange-

ment of the exciting coils, the field or exciting turns cannot be assembled and insulated before placing on the core, except in the inserted-tooth type of construction. With the milled-in-slot type, the field conductors, usually of flat strap, are dropped into the slot one at a time, with insulation between individual turns. For ease of winding, the ends are usually allowed to overhang the core, and require a very ample outside support in the very high speed machines This is illustrated in Fig. 4. The completed coils are usually held in place by strong non-magnetic wedges in the tops of the slots. These wedges are usually carried by overhanging pole tips, in the inserted-tooth type, or by grooves in the sides of the slots in the milled-slot type The design of the supports for the overhanging end windings has furnished one of the difficult problems in this type of construction Examples

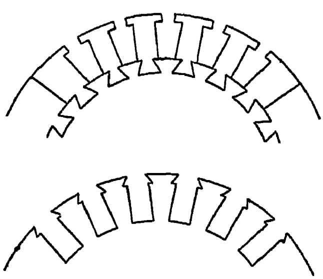


FIG. 3

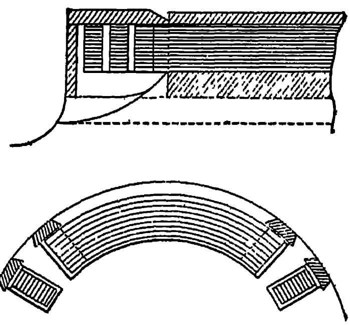


FIG. 4

of radial slot end windings, and of the rotor complete, are shown in Figs. 5 and 6.

This general construction of the radial slot type of rotor is obviously applicable to machines of any number of poles. With a two-pole machine there will be only two groups of coil slots and two groups of concentric coils, while with four poles or six poles there will be four or six groups respectively. It is evident that, with this construction, a cylindrical rotor is obtained, regardless of the number of poles. It is also evident that the problem of supporting the end windings becomes an increasingly difficult one, as the number of poles is decreased and the span of the end windings is correspondingly increased.

The support over the end windings usually consists of a heavy ring which, in very high-speed machines, must consist of material

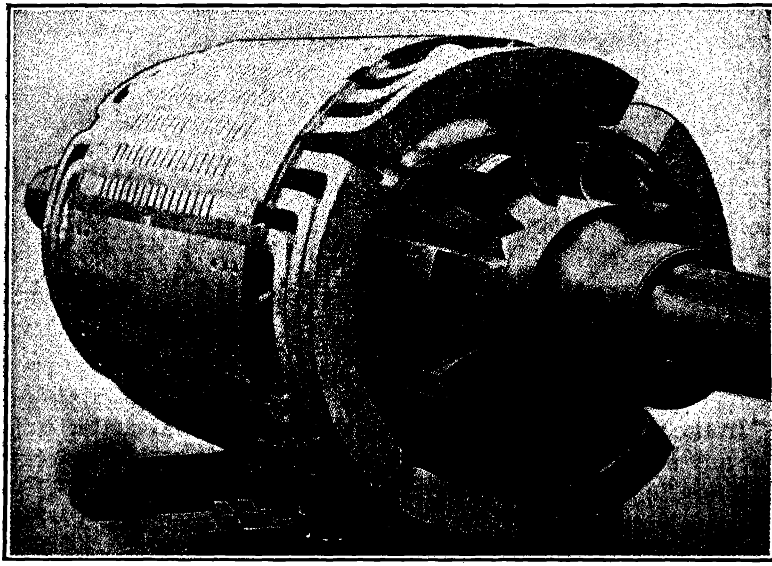


FIG. 5

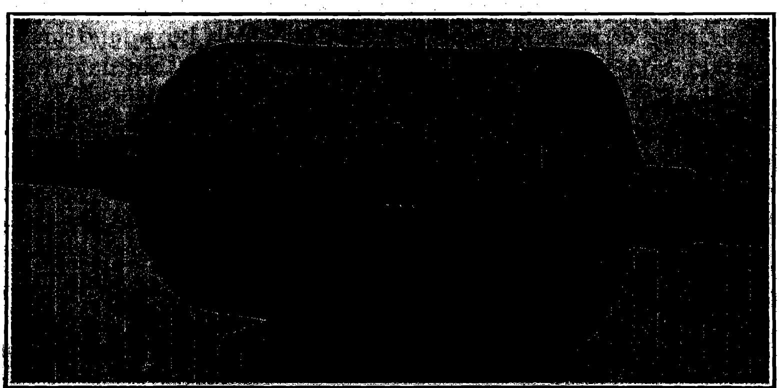


FIG. 6

having extra good physical characteristics, for this ring must not only be able to carry itself, but must also carry the weight of the underlying end windings which it supports. In the German inserted-tooth rotor, the end windings are supported by steel bands of many layers, instead of the solid steel ring. In some of the lower speed radial slot machines, such as one American type with inserted teeth, the end supports are of ring form usually made in a number of sections, which are bolted to an inner shelf by numerous bolts extending from the outer ring between the coils of the end windings to the inner shelf. While this construction is satisfactory for the more moderate peripheral speeds, yet with the much higher speeds in some of the later practise, this construction has been superseded by a solid ring type of support.

Parallel-Slot Type of Rotor

In the parallel-slot type of rotor, the slots for the exciting coils, for any number of field poles, lie in planes parallel to one another and to the rotor axis. The arrangement is illustrated by Fig 7. As usually constructed, the slots are cut across the ends of the poles, as well as in the sides, so that the exciting coils are embedded in metal throughout their length. The object of this general arrangement of parallel slots is to facilitate the winding of the exciting coils. The rotor can be placed upon a turn-table, or similar device, and rotated, to wind the coils in place under tension. Two or more coils can be wound at the same time, as is actually done in practice. As the coils can be wound under tension, and as the conductors usually consist of thin flat strap, which can be wound in very tightly, the resultant winding is a very substantial piece of work. The finished winding is supported by metal wedges over the coils.

It is obvious that, with this construction, no external support is required for the end windings, as the field core proper furnishes the necessary support. It is largely on account of this feature of well supported end windings that the parallel-slot type took a leading position during the growth of the larger two-pole, 60-cycle alternators. With the radial-slot type, the support of the end windings presented a more difficult problem in the large capacity, high-speed, two-pole machines, which, however, is being gradually solved.

In the two-pole, parallel-slot construction, in order to utilize the available winding space to advantage, it is necessary for the windings to cover the central portion of the core end where the

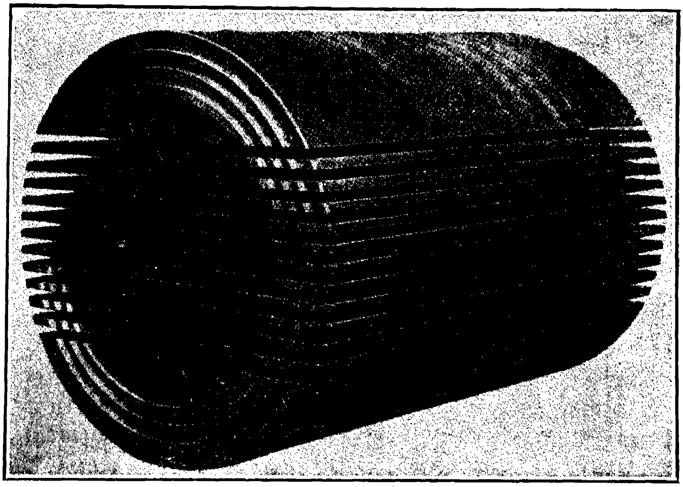


Fig. 7

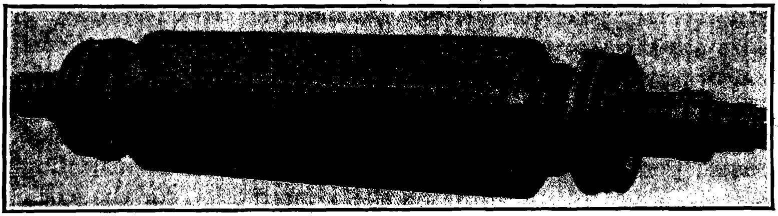


Fig. 8

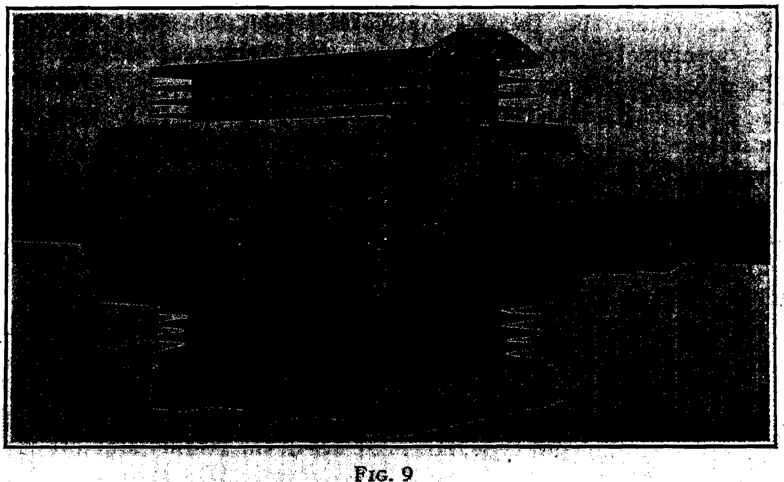


Fig. 9

shaft is usually attached, as shown before in Figs 7 and 8 Therefore, with this construction, a separate " head " or driving flange must be bolted to the core at each end, this head carrying the shaft, as shown in Fig 8. To avoid magnetic shunting of the field flux, this driving head must be made of non-magnetic material, usually of some high grade bronze, to which the shaft is attached in such a way as to keep the magnetic leakage as low as possible. This makes a good strong construction, but is necessarily rather expensive, due to the bronze driving heads. As these cost but little more for a long rotor than for a short one, the construction therefore tends toward relatively long, small diameter cores in order to lessen the relative dimensions of the bronze heads.

In two-pole, *single phase* machines of this construction, the copper cage damper for suppressing the armature pulsating reaction on the field, is comprised partly of these bronze heads, which form the " end rings " for the copper bars embedded in the slots in the rotor face.

In the four-pole, parallel-slot machine, no bolted-on driving heads are necessary, for the core proper and the shaft may be cast, or forged, in one piece, or in two or more pieces, which are bolted or " linked " together to form a solid core. The principal difference between the two-pole and the four-pole parallel slot constructions, is that the latter must have salient or projecting poles, in order to utilize the parallel construction for the slots, while the two-pole machine is preferably made cylindrical. Fig. illustrates this feature.

It is evident that there is considerable available space lost by the openings between the projecting poles, while the sections of the poles themselves are cut down very materially by the slots for the exciting winding. The limitations therefore in such a rotor are in the magnetic section of the field poles and in the available copper space, and in these features the four-pole parallel slot rotor is inferior to the radial slot type. In the two-pole machine, however, the difference between the radial slot and the parallel slot is not nearly so pronounced, as is indicated in Fig. 10 where the two arrangements are shown on one core for comparison. It may be seen from this that, in the two-pole form, the two constructions approach each other, to a certain extent, some of the slots in the parallel construction being radial, while others depart but little from the radial. One disadvantage in the two-pole, parallel-slot type, however, lies in the smaller amount of

copper space which is obtained, for the slot space must necessarily cover a less proportion of the total circumference than is permissable with the radial slot type. This winding space is limited by the physical requirements as regards bending and breaking strains in the overhanging tip *a* in Fig. 10. In the radial slot type, the slot space has no such limitation. Also, on account of the grouping of the field copper into a narrower zone in the parallel-slot type, the heat conduction from the copper presents a more difficult problem than in the radial type.

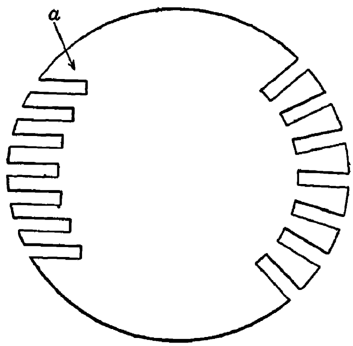


FIG. 10

At first glance, it would appear that the effective length of the field core in the parallel-slot type is very considerably diminished by the slots across the ends of the core. However, this is only an apparent effect, for the true length of the core should be taken as that inside of the winding slots, and it should be considered that the additional

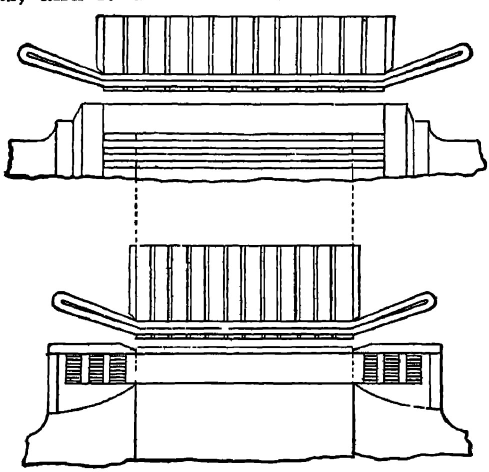


FIG. 11

length of the core at the pole face is in the nature of a coil support which takes the place of the separate support in the radial slot type. Therefore, if over-all lengths, including rotor coil supports, are compared in the two types, there is but little difference, as indicated by Fig. 11. However,

if the armature core is made of the same width as the pole face in both types of rotors, then in the parallel-slot type it will b materially greater than in the radial, for the over-hanging pol tips of the parallel-slot machine are also effective magneticall in furnishing flux to the armature. Therefore, as regards th stator, this tends toward a wider core in the axial direction, an a shallower depth of iron back of the armature slots, as indicate in Fig. 12. Also, on account of the relatively larger polar sur face, in the parallel slot type of rotor, the magnetic flux densit in the air gap is usually relatively smaller than in the radial slo type, which conduces towards a larger depth of air gap. Alsc on account of the larger polar surface, the available space fo armature slots and teeth is correspondingly increased. There fore, this type of construction is better adapted for the straigh air gap method of ventilation, as will be described later. Th greater section available for slots and teeth at the stator pol face permits a large number of ventilating ducts. The relativel large depth of gap allows a large amount of air to be fed througl the air gap to the ducts. Therefore, the " radial " type of stato core ventilation has been used very largely with this type o rotor construction. In the parallel-slot type of rotor, it is obviou that, due to the large polar surface compared with the minimun section of the field core, a limit in design is found in the magneti saturation in the field core itself.

In the four-pole parallel-slot rotor, the field section is mor limited than in the two-pole machine, due to the fact that con siderable magnetic space is lost by the notches between the pro jecting poles. However, in this type of construction, the ai gap method of ventilation is relatively easy, due to the fact tha these interpolar spaces furnish easy access of the ventilating ai to the stator ventilating ducts. In consequence, the problen of ventilation is usually not a serious one in this type of rotor Due to the polar projections, however, the tendency to noise is obviously greater than in either the radial-slot type or the two pole parallel type, which are always cylindrical.

Nothing has yet been said as to the peripheral speeds obtained in some of the actual designs of the higher speed generators. These, in themselves, indicate some of the limitations which now confront the designer.

In the 5000 kv-a., two-pole, 3600-rev. per min., 60-cycle generator already referred to, which is of the parallel-slot rotor construction, the rotor diameter is 26 in. (66 cm.) This gives a

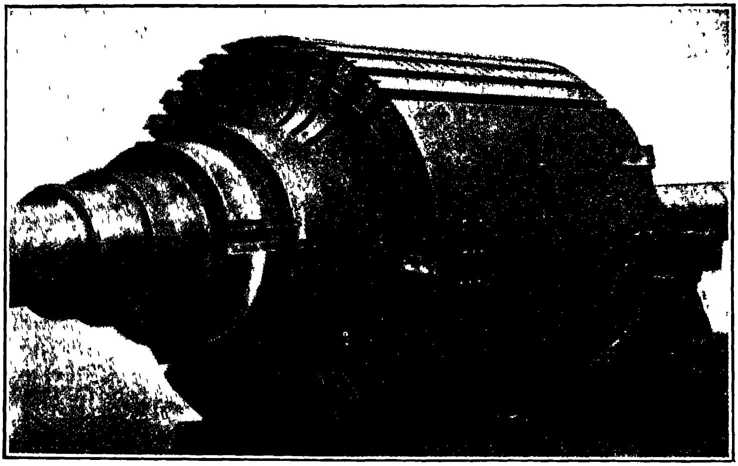


FIG. 12

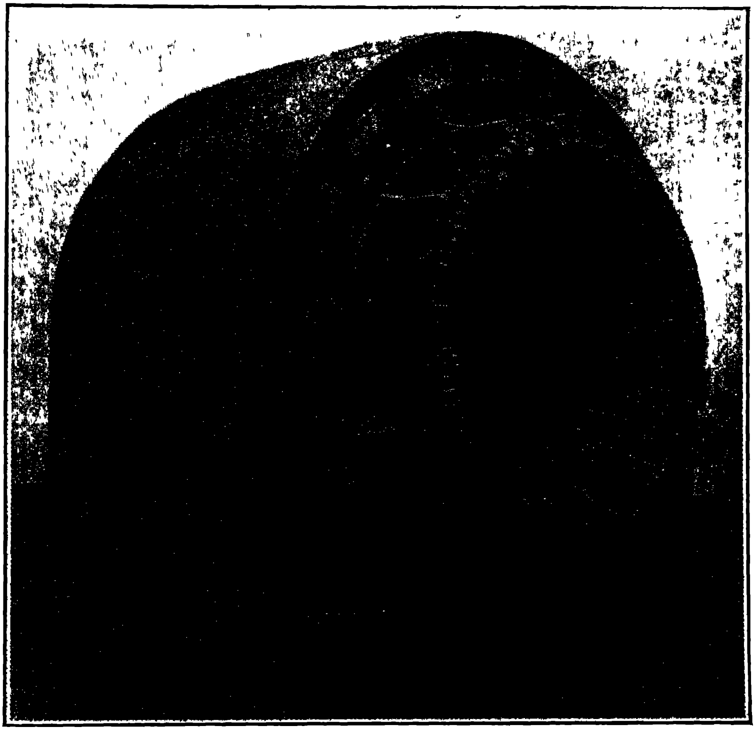


FIG. 21

peripheral speed of 408 ft. (124.3 m) per second, or approximately 24,500 ft (7468 m) per minute The core is designed for a very considerable margin of safety, and is actually tested at overspeeds which give practically 30,000 ft. (9144 m) peripheral speed at the surface of the core

In certain 19,000 kv-a , 62½-cycle, four-pole, 1875-rev per min. machines now being built, which are of the radial-slot rotor construction, the rotor diameter is 49 in. (124 4 cm) This gives a peripheral speed of 24,000 ft. (7315 m.) per minute. This compares with a speed of 21,600 ft. (6583 m.) in a 21,000 kv-a. two-pole, 1500-rev per min., 25-cycle, radial-slot machine also being built, the rotor core of which is shown in Fig. 12. Obviously the mechanical limitations are being more closely approached in the 60-cycle machines, up to the present capacities.

If a comparison is made between the above 5000 and 19,000 kv-a. rotors, with their parallel and radial type constructions, it is found that their limitations lie in quite different features. In the radial-slot type, the core stresses are much lower than in the other, but the supporting end ring is an important problem, requiring for its solution, a very high grade steel for the material of the ring. In the parallel-slot rotor, the maximum stresses are in the core itself, principally in the parts which overhang the slots at the sides and ends of the core. In the radial slot core, there are no such overhanging masses. In both constructions, the core material is purposely made of relatively soft steel, having a high percentage elongation, the object being to obtain a material which can yield sufficiently to transfer the strains from local higher points, to adjacent lower parts, and thus equalize them, to a great extent.

The smaller diameter rotor cores are made of steel forgings, in one piece. The larger cores are made up of thick steel plates assembled and bolted together to form a solid mass comprising the core and shaft extensions. By this disk construction, commercial material is used which is of uniform quality clear to the center of the disks. The fiber of the material is in a direction best suited to the directions of stress. With corresponding size disks made in one piece, the outside, to a certain depth, can be given fair physical characteristics, but the center is liable to be glass-hard, as found by experience. However, this may not be a prohibitive condition in machines of more moderate peripheral speeds. Herein lies one great difference between American and European limitations. In American practice, 60-cycles,

calling for 3600 and 1800-rev. per min machines, is the standard frequency, while in Europe, 50-cycles is standard, giving 3000 and 1500-rev. per min. machines. These lower speeds make an enormous difference in the possibilities of design and construction

Present Limitations in Design

On account of the very great capacities, at high speeds, now being obtained in turbo-generator practice, a number of problems are being encountered, the solutions of which are producing more or less radical changes, both in design and in practise. Some of the limitations now encountered are in the relatively high temperatures in certain parts, high losses in a relatively small space, the difficulty of ventilation, due to the requirement of enormous volumes of cooling air through limited openings or passages, the type of insulation, fire risks, regulation and short circuit conditions, etc.

A number of these limiting conditions, such as the temperature, ventilation, losses, and insulation, are so closely related to each other, that it is difficult to describe any one of them in detail, without including the others to a considerable extent.

The Problem of Ventilation

In the general problem of ventilation, four conditions must be considered, namely, the total loss, or heat, developed, the surface exposed for dissipating this heat to the air, the quantity of air required to carry away the heat, and the temperature of the cooling air.

In the conduction of heat from the surface of a body into the air, the quantity of heat per unit area which can be dissipated depends upon the difference in temperature maintained between the surface of the body and the body of air to which the heat is conducted. The heat dissipated raises the temperature of the adjacent air a certain amount, and thus tends to reduce the temperature difference, unless the air is renewed with sufficient rapidity. On the other hand, if the quantity of air is so great, in proportion to the heat dissipated, that there is but little rise in the air temperature, then any increased amount of air over the surface will represent practically no gain in ventilation. In other words, when the amount of air passed over a surface is sufficient to take up the heat dissipated from the surface without an undue rise, then a further quantity of air is wasteful, and it may even be considered as indirectly

harmful, in those cases where the total quantity of air is limited This has a direct bearing on the size of ventilating ducts or passages in a machine. If the air path through a duct is relatively long, then a considerable width of duct may be required in order to get the necessary quantity of air through it. On the other hand, if the air path is very short, then a very narrow duct may be most effective, for a wider duct may allow more air to pass through than can be utilized in taking up the heat.

No matter how thoroughly the ventilating air is distributed through the heat-generating body, or however effective the heat-dissipating surfaces may be, the total air supplied must be ample in quantity, or its temperature will be raised an undue amount. As the surfaces to be cooled must always have a higher temperature than the cooling air, any considerable rise in the latter will have a direct influence on the ultimate temperature which may be attained by the body to be cooled. Conversely, if an ample quantity of cooling air is supplied, but the heat-dissipating surfaces are insufficient, the ultimate temperature of the body will also be affected.

In large capacity, high-speed turbo-generators, the problem of ventilation is one of the most difficult ones encountered. The trouble lies principally in the large total loss expended in a very limited space. The difficulties of the problem may be illustrated by the following example:

Assume, in a 1500-rev. per min, 25-cycle, 15,000-kv-a machine, a total efficiency of 96 5 per cent, including air friction loss inside of the machine. This means a total loss in the machine of 565 kw., which is not excessive for this capacity, but is very large for the limited space in which it is developed A very large volume of cooling air is required for carrying away the heat due to this loss. A simple approximate rule for determining the quantity of air required is that an expenditure of one kw. in one minute will raise the temperature of 100 cu. ft (2.8 cu. m.) of air 18 deg. cent. Therefore, 565 kw. loss would require a supply of ventilating air of approximately 50,000 cu. ft. (1416 cu. m.) per minute for a rise of the out-going air of 20 deg. above that of the incoming air. Assuming a velocity of 3000 ft (914 m.) per minute, this would mean, with a cylindrical ventilating channel, a diameter of 56 in. (142.2 cm), which is greater than the rotor diameter itself. However, as the cooling air ordinarily would be supplied to both sides of the machine, the ventilating passage need only be half the above section for each side.

Obviously, such passages are prohibitively large, and much greater air velocities through the machine proper are necessary Velocities as high as 5000 to 6000 ft. (1524 to 1828 m) per minute are common, while, in some cases, more than 10,000 ft. (3048 m.) per minute has been required in certain constricted sections of the air path inside the machines Therefore, no matter how the problem is considered, it may be seen that the above condition of the enormous volume of air required, makes the problem of ventilation a difficult one

There are several methods of ventilating large turbo generators, depending upon the system of applying the air. There is, first, the radial system, in which practically all the cooling air passes out radially through ventilating ducts in the stator core. This radial system of ventilating can be subdivided into two alternative methods, depending upon whether the air is partly or wholly supplied through passages in the rotor, or through the air gap alone. These two methods are illustrated in Fig 13 The straight air gap arrangement may require a relatively large air gap, combined with very high velocity of the air along the gap, while the other method permits a considerably shorter gap. The straight air gap method of ventilation is used, to a considerable extent, in all 60-cycle machines of two-pole construction, while it is practically the only one that has been used with the parallel-slot type of machine with either two or four poles In this parallel-slot type of rotor, however, the air gap can be relatively larger than the radial-slot type of rotor, as explained before, which compensates, to some extent, for the necessity of depending upon this method entirely. In the four-pole parallel-slot rotors, the interpolar spaces are also effective. Moreover, with parallel-slot rotors in general, the openings from the air gap into the stator ventilating ducts can usually be somewhat larger in total section than with the radial type of rotor, as also described before. However, the relatively greater axial length of the core of the parallel slot type of rotor increases the length of the constricted air passages along the air gap in the two-pole machines, which is a material disadvantage

The straight air gap type of ventilation has proven astonishingly effective in cooling the rotor in both the radial and parallel-slot types of rotors, and with either type there is usually no great difficulty in forcing through enough air to cool the rotor core in a fairly effective manner. It must be considered, however, that the total rotor loss in large turbo-generators is possibly

only 10 per cent of the total loss which must be taken care of, and a relatively small proportion of the total ventilating air may suffice to cool it. According to actual measurements, corroborated by general experience, the cylindrical surface of the rotor core can give off four or five watts per square inch (6 45 sq. cm.) to the cooling air, with a temperature rise of the rotor surface of about 35 to 40 deg. cent. above the cooling air. To those who have had experience with dissipating heat from electric apparatus, this result will appear to be extremely good.

The real difficulty with the air gap method of ventilation, is not so much in getting enough air through for cooling the

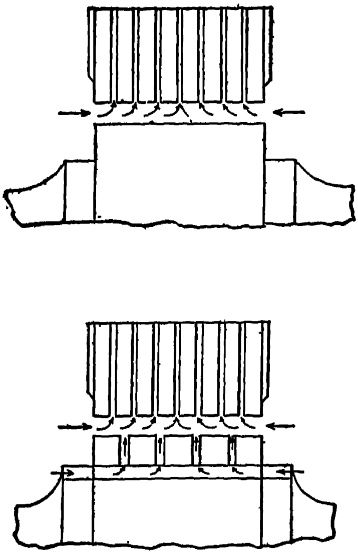


FIG. 13

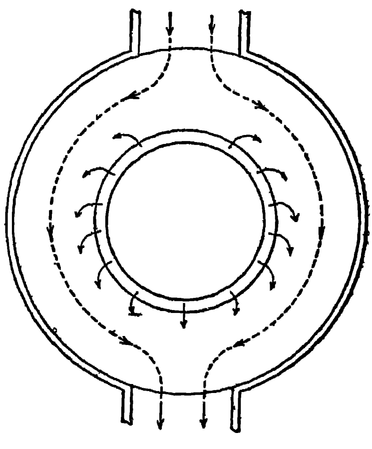


FIG. 14

rotor itself, but it is in the much larger quantity required for the stator. For instance, a one-inch (2.54 cm.) depth of gap from iron to iron) with a 50-in. (127-cm.) diameter of rotor, means a total section of air path into the gap (counting both ends of rotor) of 314 sq. in. or 2.18 sq. ft. (0.19 sq. m.). At a velocity of 10 000 ft. (3048 m) per minute, this allows a flow of only 21 800 cu. ft. (617 cu. m) per minute, which will not take care of a large machine, from the present standpoint of possible capacities with the above diameter of rotor. By additional openings in the rotor core, this might be increased to 30 000 cu. ft. (849 cu. m.) per minute, but even this is still

much less than a machine, with a 50-in. (127-cm.) diameter of rotor, would require if built for capacities otherwise possible. Therefore, on account of this limitation in the amount of cooling air, other means of ventilation have received much consideration. Two other general systems of ventilation, in addition to the gap method, have been used, namely, the circumferential method, and the axial The former has been developed and applied more extensively in the past, but the latter contains possibilities which are bringing it rapidly to the front.

In the circumferential method of ventilation, air is supplied to one or more points on the outside circumference of the stator, and is forced circumferentially around through the air ducts to suitable outlets, also on the outside surface. Air gap ventilation is usually combined with this circumferential method, partly to cool the rotor. The general arrangement is indicated diagrammatically in Fig. 14, in its simplest form, namely, with one inlet and one outlet diametrically opposite. A serious objection to this method of ventilation is found in the limited section of the ventilating path. Assuming, for example, a depth of stator core of 20 in. (50.8 cm.) outside the armature slots and a total of 40 $\frac{3}{8}$-in. (9.5 mm.) ventilating ducts, or a total effective duct space of 15 in. (37.1 cm.) width then this gives a total section of ventilating path of $20 \times 15 \times 2 = 600$ sq. in., or 4.16 sq. ft. (0.386 sq. m.). On account of the relatively great length of the ventilating path, air velocities of more than 6000 to 7000 ft. (1828 to 2133 m.) are not desirable or economical, but even with 10,000 ft. (3048 m.) velocity, the total quantity of air would be only 41,600 cu. ft. (1166 cu. m.) per minute. Furthermore, this method is handicapped in machines with very high-speed rotors, by interference between the radial and the circumferential systems of ventilation, so that the full benefit of either is not obtained. Below a certain rotor velocity, apparently the circumferential action can predominate, and the method is fairly effective up to the permissible air capacity of the stator ducts; but at very high speeds the radial ventilation may very seriously interfere with the other, so much so, that the radial ventilation alone, even with its very restricted gap section, may give as good results as the two methods acting together.

To avoid this interference, various methods have been devised, such as closing part, or all, of the radial ventilating ducts at the air gap to keep the radial effect from interfering with the other. One arrangement which has been used in Europe to a considerable

extent is indicated in Fig 15. In this, the alternate radial air ducts are closed at the outside surface, while all are closed at the air gap. The air enters by the ducts open at the back of the machine, flows both circumferentially and toward the gap, and crosses over to the immediate ducts by axial openings back of the armature teeth, and then along these ducts to the outlet. This scheme is effective in principle, but is uneconomical in the sense that less than the total section of stator ducts is useful, as regards the quantity of air which can be carried. There is usually one large central duct to allow an outlet for the rotor ventilating air. This particular arrangement of the stator also uses axial ventilation in crossing over from one set of ducts to the other, which is an effective arrangement.

A modification of the simple circumferential method of

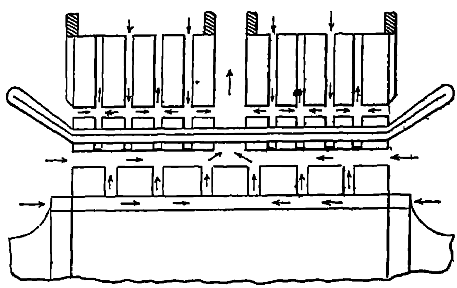


FIG. 15

ventilation is to admit air to the back of the stator at two opposite sides of the machine, and deliver it at two outlets at intermediate points on the surface, as shown diagrammatically in Fig. 16. By this means, the cross section of the ventilating path is doubled and the length is halved. Also, the interference of the radial ventilation with the circumferential will be less harmful. A serious disadvantage in the circumferential ventilation in general is that the ventilating path is relatively long, especially where there is but one inlet and outlet, and therefore the cooling air at the outlet of the channel may be considerably hotter than at the inlet, with consequent less effective cooling action. This means points of local higher temperature in the core, due to the method of ventilation. In the radial type of ventilation, the coolest air is applied near the seat of the highest losses, namely, at the armature teeth, and immediately back of

them, and the air, as it becomes heated, passes over the outer part of the iron which has a diminished loss, and therefore normally less heat to dissipate. Therefore, the effect of the increased temperature of the cooling medium is offset by the lower loss and consequent less necessity for ventilation, in the part where the air is hottest. The radial system of cooling is therefore theoretically the most effective, but practically, the difficulty is in applying it, due to the limited air passages available.

Both the circumferential and the radial methods of cooling are subject to one serious defect, namely, most of the generated heat in the stator iron must be conducted across the laminations to the air ducts. The rate of conduction across the lamina-

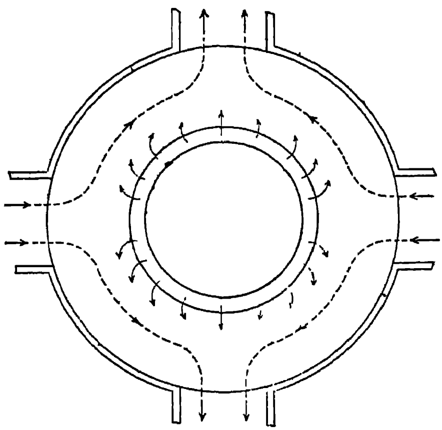


FIG. 16

tions is only from 1 per cent to 10 per cent as great as along the laminations themselves, according to various authorities. Therefore, if the heat could all be conducted along the laminations to the ventilating surfaces, apparently much more effective heat dissipation could be obtained, provided sufficient surface is exposed to the air, and an ample quantity of air supplied. This has led to the development of the axial system of ventilation, as distinguished from the radial and circumferential. In this method, a large number of axial holes are provided in the stator core which may extend uninterruptedly from one side of the core to the other, or they may extend from each side to one or more large central radial channels which form the outlet. The usual numerous radial ducts are omitted, or may be con-

sidered as combined in one central channel. This general arrangement is illustrated in Fig. 17. The rotor cooling is accomplished by air along the air gap, and through the rotor core to the large central duct. In this method of ventilation therefore, there is a combination of two types, namely, the axial and the air gap, but there is not the interference between the two, that is sometimes found where the circumferential method is used.

From the preceding, it may be seen that the problem of putting a sufficient quantity of air through the machine is an extremely difficult one. In addition, in very large machines, the problem of supplying the required quantity of air from a suitable blower forms another serious problem. In smaller capacities, and in slower speed machines, it has been the usual practise to attach blowing fans to the rotor shaft or core, as

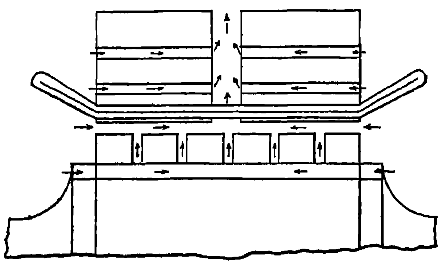


FIG. 17

part of the outfit. There is no particular difficulty in this arrangement, except, possibly, in the high-speed construction of the fans required for 60-cycle, two-pole machines. Such fans can supply an amount of air which is limited by the diameter and other dimensions of the fan itself.

Assume, for example, that by lengthening the rotor core, or by other modifications in the construction, the capacity of the machine can be doubled, and therefore double the quantity of air is required for cooling. If the limit of the fan design or operation was reached before, then obviously some radical change is required with the new capacity of the machine. This condition apparently has been reached in some of the later practise in large, high-speed turbo-alternators. One obvious solution of this difficulty lies in the use of separate slower speed, large diameter, fans or blowers. This may appear to be a step backward, but when the above conditions and limitations are

taken into account, it is not so. The "tail" must not be allowed to "wag the dog;" the blower, which is an adjunct, must not be allowed to dominate the construction of the machine itself. Moreover, there are a number of meritorious features in the use of a separate blower. In the first place, it can be made somewhat more efficient than the high-speed, rotor-driven fans. Again, with a suitable means to drive, variable speeds, and therefore different air pressures, can be obtained. This feature may prove to be very desirable or advantageous under peak, or overload, or emergency conditions.

One further condition keeps cropping out in the general problem of ventilation, namely, that of filtering or washing, or otherwise cleaning the ventilating air With 50,000 to 75,000 cu. ft. (1415 to 2122 cu. m.) of air per minute passing through a large machine, obviously in a year's time, an enormous quantity of foreign matter is carried through the machine with the ventilating air. A deposit of a very small per cent of this in the machine will probably be disastrous. In fact, however, the high velocity of the air through the machine serves to keep the air passages clear if no oil or moisture is allowed to enter. That a large amount of foreign matter does go through the machine is very soon shown in case a little oil is allowed to get into the ventilating passages. This oil catches the dirt and in a short time the ventilating passages may be very materially obstructed.

On account of the deposit of dust, etc. in the ventilating passages, it is necessary to clean certain types of machines at more or less frequent intervals, and it is advisable to clean all types occasionally. With some systems of ventilation, where such cleaning is difficult, or almost impossible, such as that shown in Fig. 16, provision must be made for cleaning the air before it enters the machine. With the particular construction shown in Fig. 16, air filters are almost always supplied. In the American types of construction, however, such filters have not yet been used, except in a more or less experimental manner, due probably to the greater accessibility of these machines as regards cleaning. But such filtering processes possess considerable merit in general. One modification which is being agitated at present is that of washing, instead of filtering, the air. This serves the double purpose of cleaning and cooling the air, and in very hot weather, when the available capacity of the machine is at its minimum, this cooling effect may mean a reduction of 6 to 10 deg. in the temperature of the machine.

THE TEMPERATURE PROBLEM

In the general problem of temperatures in electrical apparatus, it is not the rises, but rather the ultimate or limiting temperatures which are of first importance. Furthermore, the real limitation in ultimate temperature does not lie in the copper and iron, but in insulating materials used; and only insofar as the temperatures of the former affect the latter do they concern the general problem. However, as insulating materials in themselves are not usually sources of heat, but as they receive most of their heat from adjacent media, such as iron or copper which may be generating loss, the real temperature problem, as regards insulation, resolves itself into the consideration of that of the adjacent materials. Therefore, it is one which, for its full analysis, requires a knowledge of the sources and amounts of heat generated, and its conduction and distribution to other parts

Broadly speaking, there is always a flow of heat from points of higher to those of lower heat potential and the amount of flow is also a function of the quantity of heat generated, the section and length of the paths through which it can flow, and the specific heat resistance of the various materials which conduct the heat. In an electric generator, for example, heat is generated in large quantities in the armature teeth and in the armature core It is also generated in the armature coils when the machine is carrying load Part of the armature copper is buried in the armature slots where it is almost surrounded by iron, which, in itself, develops a loss, while another part, such as the end windings, may be surrounded by, and thoroughly exposed to, the ventilating or cooling air In such end portions, the flow of heat will usually be from the inside copper, directly through the insulation to the cooling air The amount of heat which will flow from the copper through the insulation, depends upon the temperature differences between the copper and the outside surface of the insulation, upon the cross section of the path of flow, upon the thickness and "make-up" of the material, and upon the heat-conducting properties of the insulation itself There is also a considerable temperature gradient from the outside surface to the air. If the surrounding air is not renewed with sufficient rapidity, the flow of heat from the insulation to the air may raise the temperature of the adjacent air, so that the total temperature drop is decreased, and the amount of heat dissipated is correspondingly reduced.

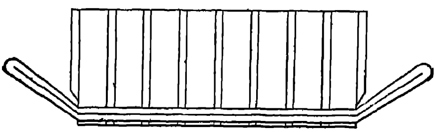
In the armature core, the problem is much more complex

In the copper buried in the armature slots, there are usually three paths along which the heat can flow. First, it may flow from the copper directly through the insulation to the iron, provided the adjacent iron temperature is lower than that of the copper. Second, it may flow lengthwise of the copper to the end windings to be dissipated directly into the air from that portion of the winding, as described above Third, in the case of open-slot machines, one edge of the coil may be exposed to the air in the air gap, and there may thus be a direct conduction of the heat through the insulation to the air in the air gap. This latter case, however, only holds for the upper coil, or that next to the gap, in the case of two coils per slot, which is the most common construction In the bottom coil, the only means of conduction in the buried portion of the coil, are to the adjacent iron or lengthwise to the end windings, or to the adjacent upper coil, which, however, would normally have at least as high temperature as the lower coil Therefore, the two effective paths should be considered as through to the iron and thence to the air, and lengthwise of the copper to the end windings and to the air. It is the relation of the various factors of these two paths that control the actual temperatures.

It has usually been considered that, in the buried copper, the greater portion of the heat is conducted directly into the surrounding iron. This, however, is only partially true, depending upon many features in the construction and type of apparatus, The heat conductivity of copper is, roughly, about six times that of laminated iron lengthwise of the sheet, which is possibly ten to twenty times as great across the laminations. In an armature which is comparatively narrow and which has very open, well ventilated end windings, a relatively small difference in temperature between the copper at the center of the core and that in the end windings, may cause a relatively large flow of heat from the buried copper to the end copper. Therefore, in certain designs, a great part of the armature copper heat may be dissipated through the end windings, and not through the armature core, especially in those cases where the armature core in itself has a considerable temperature rise. There even might be no conduction of heat from the copper to the iron, or there may be conduction from the iron to the copper; for if the copper is at the same temperature as the iron at the center of the core, for instance, then at each side of the center, or as the edges of the core are approached, the copper temperatures will be relatively

lower than at the center, and therefore lower than the adjacent iron, on the assumption that the iron temperatures would be practically constant over the full width of the core The conditions would therefore be as represented in Fig. 18. The solid line *a* in this figure represents the iron temperature at uniformly 40 deg. cent. rise, and the dotted line *b* represents the copper temperatures from the center of the core to the edges. The temperatures at the center being assumed the same for copper and iron, obviously there will be a flow for heat from the iron to the copper near the edges of the core. The effect of this additional heat carried out by the copper would be such as to tend to increase the temperature of the copper at the center of the core by "banking up" the copper heat.

Again, if the temperature of the copper at the center is materially higher than that of the surrounding core, the conditions may be as represented in Fig. 19 In this case, assuming the core at constant temperature, there will be heat flow from the copper to the iron at the center of the core, and from the iron to the copper at the edges



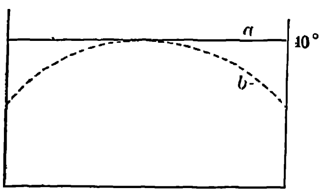


FIG. 18

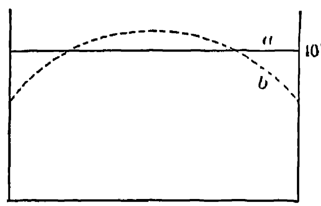


FIG 19

This study of the problem leads to certain very curious conditions which are sometimes found in large machines. At no-load, for instance, with practically no copper loss present, and with high iron loss, there may be a very considerable flow of heat from the armature teeth through the insulation into the copper, and thence to the end windings and to the air. In this way the temperature of the armature teeth at no-load, and with normal voltage generated, may be considerably reduced by conduction of the iron heat into the copper, while the copper itself

may show a very considerable temperature rise. When load is placed upon such a machine, sufficient to raise the temperature of the copper up to that of the iron in the armature teeth, the latter is actually increased in temperature, due to the prevention of the heat conduction into the copper. In this way, therefore, the copper may apparently heat the iron, although there is no direct flow of heat from the copper to the iron, but the reverse flow is prevented.

In high-voltage windings requiring thick insulation, the temperature drop from the copper to the outside may be relatively large; that is, with a given difference of temperature between the copper and the surrounding air, a relatively small amount of heat may be conducted through the insulation. Experience shows that the amount which can be conducted is a function of the quality of the material, the way it is built up, its thickness, and also the pressure upon it. It is almost impossible, in a machine in service, to calculate exactly the flow of heat, even if all the temperature conditions are known, for the insulating material itself is one of the variables in the problem The ability of the insulation to conduct heat will change with operating conditions, to some extent, as, for instance, it may tend to expand somewhat under heat, and thus change its heat conducting qualities.

In the armature iron, the problem of heat conduction is just as complicated as in the armature conductor. The principal sources of heat lie in the armature teeth and in the armature core back of the teeth. As a rule, the loss in the portion of the core immediately back of the teeth is relatively greater than at a greater depth, for the magnetic fluxes which cause the temperature rise, generally crowd close to the teeth, so that the density is higher at such parts.

The heat from the armature teeth can be dissipated along several paths. It can flow lengthwise of the laminations to the end of the tooth and into the air gap, where the ventilation is usually fairly good, but the tooth surface exposed is relatively small. In the second place, it can flow back along the laminations to the armature core where it can spread out through a path of much greater cross section and be conducted partly to the back part of the laminations, and partly transversely to the ventilating ducts. A third path from the armature teeth is across the laminations of the teeth, to the neighboring ventilating ducts. This latter path, however, must necessarily be relatively poor

in conductivity per unit section of path, compared with the others, but offsetting this, it is frequently of much greater cross section and of relatively small length. In passing from plate to plate, the heat must pass through the insulating varnish, or other material used, which is of relatively high heat resistance compared with the iron itself. Nevertheless, in machines with radial ventilation, a very considerable portion of the heat due to the tooth loss is carried transversely through the plates to the air in the ventilating ducts, simply because that is the path of lowest total heat resistance, everything considered. In many cases, the temperature in the core back of the teeth may be as high as that of the teeth themselves, so that the only flow possible is across the laminations to the air ducts, or lengthwise to the tip of the teeth in the air gap. Therefore, the question whether the armature teeth may be hotter than the armature core, or whether the flow of heat is from the teeth to the core, or from the core to the teeth, is a very involved one; and yet upon this question depends, to a great extent, the temperature rise in the buried armature copper. If the armature core is normally hotter than the teeth, and a considerable amount of heat in the teeth is carried away by the buried copper at no load, then it may happen that when carrying heavy load, the heat in the teeth will rise very considerably above the no-load condition, and it may actually so "bank-up" that there is still more or less flow from the iron to the copper, even with load. With such a condition, therefore, the outside of the insulation may reach a higher temperature than the inside, while in those cases where the temperature of the copper rises above that of the iron of the armature teeth, the inside of the insulation will be hotter. Therefore, the temperature to which the insulation is liable to be subjected appears to be largely a problem for the designer to determine from his calculations, based upon accumulated data and experience. This is especially the case with very wide armature cores and large, heavily insulated armature coils, such as found in large capacity, high speed turbo generators. In such machines, experience has shown that various temperature conditions may be found, depending upon the location and relative values of the losses in the different parts and the means for conducting away the heat. Tests have shown that, in some cases, the armature iron at the center of the core is considerably warmer than the armature copper, while in other cases the opposite is found to be true.

In such apparatus, the temperatures actually obtained are liable to be materially higher than the usual methods of measurement will indicate. These temperatures are inherent to the conditions of design and cannot be avoided economically, in certain types of apparatus, such as turbo-generators. In such machines, the limitations in speed, strength of material, etc. force the designer to certain proportions which preclude larger dimensions, or lower inductions in the iron, or lower densities in the copper, or increased ventilation. In such apparatus therefore, the development apparently lies in the direction of insulations which will stand the higher temperatures which may be obtained.

These conditions of higher temperatures in some parts of the machine, than indicated by the usual tests, have been recognized for years by designers and manufacturers of large electric machinery. A rough indication of these temperatures can be obtained by exploring coils or thermo-couples suitably located. However, it is evident that such coils, if located next to the copper, will not give the correct temperature measurement if the flow of heat is from the iron to the copper, while a coil next to the iron will not give the correct result with the flow from the copper to the iron. Experience has shown that the temperatures, in corresponding positions around the core, may not be uniform, due to local conditions. In consequence, it is not practicable to actually determine the true temperatures of all parts of the insulation on commercial machines, except by measurements of a laboratory nature, which would involve such a number of separate readings as to be commercially prohibitive.

On account of the higher temperatures which may be found in such apparatus, and the difficulty of making exact measurements, except by laboratory methods, manufacturers very generally have adopted the use of mica as an insulating material on the buried part of the coils. Experience has shown that such material, when properly applied, can safely stand temperatures of at least 125 deg. cent. How much more has not yet been determined.

Of such machines it may be said that the manufacturer, with his guarantee of 40 deg. cent. by thermometer, actually builds for possible temperatures of 70 to 90 deg. cent. in some parts of the machine, for he expects to find fairly high temperatures in some cases with exploring devices. The usual guarantee of 40 deg. cent. therefore should be considered as only a relative indication of a safe temperature in such apparatus.

If, for instance, the exploring coils should show 70 deg. cent. maximum rise under running conditions, and the permissible ultimate temperature of fibrous or tape insulation is assumed as 90 deg. cent. for continuous operation, then obviously, with air at 40 deg. cent. the insulation would be considered as insufficient from point of durability, except for intermittent service, such as overloads, and such limited conditions. Plainly, the insulation, for such temperatures, should be of mica, or equivalent material, for which 125 deg. cent. has been found to be safe.

Furthermore, it may be stated that with such mica insulation, a turbo generator which shows 75 deg. cent. rise by exploring coils, or thermo-couples, has, in fact, more margin of safety than the ordinary varnished-tape-insulated low-voltage machines of any type, which show 40 deg. cent. rise by thermometer or 50 deg. cent. rise by resistance.

The foregoing aims to bring out clearly that the temperature problem is a most complex one, in all electrical apparatus, and especially so in turbo-generators. It indicates that no simple temperature test can show all the facts, and that all commercial methods must be considered as approximations. It also shows the absurdity of classifying a piece of apparatus as *good* or *bad*, respectively, according to whether it tests possibly one or two degrees below or above a specified thermometer guarantee. Also, following out the above principles on heat flow, various fallacies in temperature measurements might be noted. For example, it is usually assumed that, after shutdown, if a gradually rising temperature is shown, this is a more accurate indication of the true temperature. But this may be entirely wrong as regards windings. If, for instance, the core back of the armature slots is materially hotter than the armature teeth while carrying load, then, upon shut-down, with the air circulation stopped, the teeth will rise to approximately the same temperature as the core back of the teeth, and there may be a flow of heat into the coils, which condition may not have existed while carrying load. A thermo couple on the coil or in the teeth would thus indicate a false temperature rise after shut-down. This is cited simply as one of many instances, to show the possibilities of entirely wrong conclusions which may be reached in the problem of temperature.

The Insulation Problem

The one fundamental condition which must be considered in the insulation problem, is the durability of the material itself, and

this must be viewed from two standpoints,—the mechanical, and the electrical. From the mechanical standpoint, the material may have its insulating qualities impaired by the action of mechanical forces which tend to crack, or crush, or disrupt the material itself, or it may be affected by being permeated by foreign materials or substances, or it may be injured by such overheating as will partially or wholly carbonize it, or render it brittle or otherwise unsuitable for the desired purpose.

From the electrical standpoint, it may be weakened by deterioration of the quality of the insulating material itself or some of its component parts, which may be due to heating, or oxidation, or many other causes.

The effect of mechanical injury, such as cracking crushing or overheating, on the insulating qualities, will depend upon many conditions. In some cases, with relatively low voltage, any effective mechanical separation of the parts is sufficient for electrical purposes. For higher voltages, continuity of the separating insulating medium is necessary.

Experience has shown that, for moderate voltages, temperatures which may injure, or even ruin, the insulating material, from a mechanical standpoint, may not seriously affect its insulating qualities. Many insulating materials of a cellulose nature will still retain good insulating qualities if maintained at temperatures as high as 150 deg. cent. for such long periods that the material itself semi-carbonizes. Under such high temperature conditions, however, it becomes structurally bad,—that is, it may become so brittle that it tends to crumble, or powder, or flake off, and thus its value as an insulation is impaired by displacement of the material itself. In low voltages, therefore, it is not a deterioration in the insulating qualities, but rather a mechanical breakdown of the material itself, which is liable to cause trouble. With high voltages, however, the conditions may be quite different. With some insulating materials, the dielectric strength may be so affected by long continued high temperatures that the insulating quality becomes insufficient. This has a direct bearing on large capacity, high-voltage turbo-generators.

In the problem of insulation, certain difficulties have been encountered in large turbo-generators, which, while they would have developed eventually in other large machines, yet became apparent more quickly and prominently in the turbo type, due to the abnormal conditions in its design. The two most promi-

nent difficulties were, first, that of relatively high temperature in the buried copper, already described, and second, the destruction of the insulation by reason of static discharges between the coils and the armature iron

Due to the fact that the ultimate temperature reached in such machines not infrequently exceeds the safe limits for insulation of the fibrous or cellulose type, such insulations will show deterioration eventually in their insulating qualities and their durability. In consequence, with the advent of the larger machines, it became necessary to return to the use of mica for insulating purposes on the buried part of the coil This type of insulation in the form of mica wrappers, had been used extensively on some of the earlier large capacity, slow-speed generators, but it had not been adopted on large turbo-generators, due principally to the difficulty in applying the very long wrappers for the straight part of the coil. However, when the gradual deterioration of the fibrous type of insulation was noted in large turbo-generators, the mica wrapper type of insulation was again taken up and, after considerable experiment, was applied successfully for the outside insulation on the straight parts of the coils This use of mica overcame the deterioration in the insulating qualities of the outside insulation, but for a while it was considered that a fibrous type of insulation was still effective between turns in those coils where there were two or more turns in series per coil. As stated before, the insulating qualities of many fibrous materials will stand up astonishingly well under low voltages, when the material is apparently so greatly heated that it is practically carbonized. Therefore, temperatures which did not carbonize, but simply browned, or darkened, the material, had not been considered dangerous, and undoubtedly many thousands of electrical machines of all kinds are today in operation, in which the insulation is in this condition, and in which no trouble need be expected. For this reason, little or no trouble was expected between turns on the turbo-generators. However, a new condition was encountered in large capacity machines, namely, the insulation between turns, when it became dry and brittle at the higher temperatures, was liable to be injured by the terrific shocks to which the coils were subjected in such machines, in case of a short circuit across the terminals. The insulation would be cracked, or so distributed that short circuits would occur later, without apparent cause. These short circuits on large machines,

most often appeared as breakdowns to ground, even with the mica wrapper insulation on the outside of the coil Incidentally, several cases were discovered where arcs had occurred inside the coils between adjacent turns, and where they had not yet broken through the outer insulation to ground. For many months the writer, with his associates, followed up this matter, examining all available coils and windings. Eventually the conclusion was reached that many of the breakdowns to ground had actually started between turns on the inside of the coil. Moreover, as a corroboration, it was noted that in machines with one conductor per coil, the breakdowns were practically negligible. This investigation led to the practise of insulating the individual turns, in each coil, from end to end, with mica tape. After the adoption of this practice, it is noteworthy that the breakdowns to ground practically disappeared, although the outside insulation to ground had not been changed in type or thickness.

Many improvements have been made in recent times in the application of this mica insulation. One of these is the Haefely process, developed in Europe, but now being used extensively in this country. By this process, the mica wrappers are so tightly rolled on the coil that practically a solid mass of insulation, of minimum thickness and greatest heat conductivity is obtained.

By means of the mica insulation, the temperature difficulties in general have been entirely overcome, and a durable and non-deteriorating construction, from an insulation standpoint, has been obtained with the temperatures which appear to be more or less inherent in the large, high-speed turbo-generators.

The second trouble, namely, that due to static discharges between the armature copper and the iron, was also encountered to a certain extent, on some of the earlier machines. It was found that these discharges were apparently "eating" holes, or even grooves, through the outside insulation of the armature coils. This effect was most pronounced at the edges of the air ducts and at the ends of the armature core, where edges were presented by the iron. After a long period, the holes or grooves would become so deep that the insulation was weakened or ruined.

This was a very disturbing condition, when it was once fully recognized and appreciated. Again, a comprehensive investigation was made to discover a cure for this difficulty. Various types of machines and windings were examined. It was noted

that the action was a function of the voltage of the machine, but was noticeable, in some cases, at relatively low voltages. During the course of the investigations, it was noted that where mica wrappers were used with an outside layer of tape, the " eating away " extended only through the outside wrapping in as far as the mica, and that no apparent effect at the mica was visible. Even when examined with a very powerful microscope, no evidence of any puncture of the mica was found, in any case These investigations naturally led to the conclusion that the most suitable remedy for the trouble was the use of mica insulation, which was also a remedy for the temperature conditions This is one of the rare cases in large turbo-generators where two desirable conditions do not conflict with each other. The mica insulations on the buried part of the coil has now been very generally adopted in this country on high-voltage machines, whether of the turbine-driven, or any other type

This static trouble was considered so serious at one time that low voltage practice with step-up transformers was adopted by some manufacturers as the safest course, until something positive in the way of a remedy was proved out. This trouble promised to be one of the most serious encountered in high-voltage generator work, and even threatened to revolutionize practise in winding generators for the higher voltages. However, as consistently advocated by the writer, the use of mica, suitably applied, appears to have entirely overcome this trouble, as evidenced by several year's experience, and all indications now are that there need be no fear from static discharges on windings of 11,000 and 13,000 volts. Even in the 11,000-volt New Haven generators with one terminal grounded, which gives the equivalent of a 19,000-volt, three-phase winding with the neutral grounded, the mica insulation appears to be successful and durable.

Rotor Insulation

In most of the early turbo-generators, the rotor winding in the slots was insulated with fibrous material, " fish paper " and " horn " fiber having the preference. One of the difficulties in the rotor is that the insulation between the winding and the slot is liable to be crushed or cracked by the high centrifugal forces. In the earlier insulations, before fish paper was used, it was found that even at very moderate temperatures, the insulation got dry and brittle, and cracked readily. Fish paper, or horn fiber, was then adopted pretty generally. Such material

apparently stood much higher temperatures than the ordinary fibrous insulations. However, experience also showed that eventually this also became brittle, and was liable to be cracked, and then displaced, due to the centrifugal forces. There is always the possibility of a small amount of movement in the field coils when a machine is being brought up to speed, and this movement, in itself, may eventually damage the insulation if it is at all brittle.

As the capacities and speeds of turbo-generators were increased and the space limitations for the rotor windings became more pronounced, the resulting higher normal temperatures led to the adoption of mica for the insulating material in the slots with either mica or asbestos for the insulation between turns. As the voltage between adjacent turns is always extremely low, what is needed is really a durable separating medium, rather than an insulation, this medium being one which will not become crisp or brittle at fairly high temperatures. Asbestos has served for this purpose very effectively, and even has some advantages over mica, as the latter must be applied in relatively small pieces in the form of strap or tape, and the individual pieces are more readily displaced or shifted than is the case with asbestos. Some very severe tests have been made in order to determine the possibilities of such rotor insulation In one case, a turbo rotor thus insulated was run at full speed for over 40 hours, with such a current that the rise by resistance in the rotor copper was about 250 deg. cent It was the intention to continue this test very much longer, but the conduction of heat from the winding to the core, and thence through the shaft to the bearings, was such that finally the bearings became overheated and gave out. After this test, the winding was carefully dismantled, and no evidence of any injury to the insulation could be discovered. Of course, such temperatures are not recommended in turbo rotor practice, but this was simply an attempt to find a temperature limitation. If a designer wants to find the facts in any apparatus, he will obtain the most valuable information if he operates the apparatus up to the point of destruction. He thus fixes a limit which he must keep below.

The use of mica, or mica and asbestos, on turbo rotors has been very generally adopted in this country at the present time, and it may be said that, within the writer's experience, no case of destruction of one of these windings through heating, has

come to his notice, although a great number of them have been in service for a relatively long time. In many of the older machines with fish paper insulation in the rotors, the conditions of ventilation and the normal ratings of the machines were such that the maximum temperatures in the rotor windings were relatively much less than in present practise It may therefore be said that the use of mica in the rotor has been largely due to the introduction of the larger capacities and higher speeds.

Losses in Turbo Alternators

The total iron and copper losses in a large, high-speed turbo-alternator are in general no higher than in a corresponding capacity low-speed machine

As far as the iron losses are concerned, no further comment need be made than that the magnetic flux densities in general are somewhat lower than in lower speed machines of same frequency, and therefore the losses per unit volume of material are no larger.

The total armature copper losses in turbo-alternators, as a rule, are considerably smaller than in corresponding capacity machines of the moderate or low-speed types. This is due partly to the use of a smaller total number of conductors, and partly to a lower current density in the armature conductors. As brought out before, in a narrow core machine, a considerable portion of the buried copper heat may be conducted lengthwise of the conductor into the end winding, and there dissipated into the air In the turbo-generator, with its much wider core and greater distance from the buried copper to the end windings, a smaller percentage of the buried copper heat will be conducted into the end windings. To partly compensate for this, it is usual to work the armature copper in the turbo-generators at a lower current density, and therefore at a relatively lower total copper loss. This is somewhat of a handicap in the economical design of the generator, as extra space is thus required for the armature winding. In some of the earlier machines, the armature conductors were made of solid copper bars of relatively large section, partly for stiffening or bracing the end windings, as will be referred to later With these solid conductors there was a very considerable loss in the buried copper due to eddy currents. To compensate for this, the armature conductors were made very large in section, so that the current density, due to the work current alone, was very low compared with

practise in other types of machines. On account of the comparatively large section of armature conductors, the conduction of heat from the buried copper to the end windings was relatively large. In some of these earlier, large capacity machines, the nominal current density in the armature conductors was so low, and the section of conductors so great, that the total buried copper loss, due to the work current, could be carried from the buried part of the coils into the end windings with a comparatively small drop in temperature, so that, if there had been no eddy currents present, the buried copper would have shown less rise than the iron. Any considerable rise which occurred was thus chargeable to eddy currents in the buried conductors, rather than to the work current. While such construction was fairly effective for the purpose, yet it was decidedly uneconomical in design, as indicated before. In fact, with later proportions and methods of design, the safe outputs of some of the earlier machines could easily be 50 to 75 per cent greater, largely on account of elimination of eddy currents and improvement in methods of dissipating heat from the end windings. In many of the older machines, the ventilation of the end windings was not nearly as effective as in modern types, due principally to the form and arrangement of the end connectors. Usually air spaces were allowed between adjacent coils although, in some instances, these were so small as to give but little benefit. Moreover, in many cases, the type of end winding employed rendered these air spaces between coils rather ineffective, unless special means were taken to deflect the air between the coils. With later constructions, the end windings lie more or less across the path of the ventilating air, and there are ample openings between the coils, so that a very considerable part of the ventilating air will actually pass between the coils of the end windings in such a way as to give the maximum possible ventilation. When it is considered that the total armature copper loss may be only 20 per cent of the total stator loss, it will be seen that an excessive amount of air is not required when the end windings are properly arranged for most effective ventilation.

Much effort has been expended in eliminating or reducing the eddy current losses in the buried copper of large turbo-generators, as well as in other types of large capacity alternators. These eddy currents are due to two sources, namely, the alternating magnetic flux across the slots due to the armature ampere

turns per slot, and secondly, the magnetic fringing from the rotor pole face into the open armature slots. In some instances, tests have indicated that the local e.m.fs. set up in the armature conductors by the flux through the slot opening is very consider ably greater than those due to the flux across the slot. Obviously with partially closed slots, this fringing into the top of the slot should be practically absent.

The simplest remedy for the eddy currents set up by these local e.m.fs. is to sub-divide the conductors into a number of wires or conductors in parallel, so arranged or connected that the local e.m.fs. oppose and, to a great extent, balance each other. This opposition may be obtained by special arrangement of the conductors in each individual slot, or parallel conductors in the two halves of a complete coil may be connected in opposition to each other. Some of these arrangements do not completely balance the opposing e.m.fs., but they include the resistance of the complete coil in the eddy current circuit, so that the eddy losses are not only very materially reduced, but they are distributed over the entire coil, including the end windings, which condition, in itself, represents a very material improvement.

Protection Against Fire

An important problem connected with the insulation of large turbo-generators, is found in the fire risk, or danger of destruction of the end windings due to starting an arc at some point. On account of the tremendous ventilation in such machines, a fire, if once started, may quickly ruin the entire end winding. An extended investigation was made, with a view to providing an insulation which would not burn rapidly. Among other tests, the end windings were finished on the outside with an asbestos covering or tape However, such tape requires some sort of sealing varnish, or material to fill its pores, to keep it from absorbing moisture or oil. The tests showed that if a fire was once started, combustion would be maintained by the gases liberated by the "gasification" of the varnishes and other material in the end windings, whether the coil was covered with asbestos or not. No covering which was tested appeared to be very effective. Although some outside covering might be found which would be slightly effective in preventing fire from starting so readily, yet, if once started, it appears that a fire can very easily maintain itself in such machines. Eventually, the conclusion was reached that the safest course would be to

provide suitable closing doors or valves in the air inlets to completely shut off the incoming air to the machine. In addition, suitable doors on the air outlets, where they can be applied, should also be helpful, by retaining the smoke and burnt gases inside the machine, which thus assist in smothering the flames. The use of fire extinguishers of the gaseous type will usually be rather ineffective, unless the incoming air and ventilation is practically cut off. For instance, with 60,000 cu. ft. (1698 cu. m.) of air per minute passing through a large machine, the addition of a little gas for extinguishing the fire would hardly make any impression. In one instance, in attempting to extinguish a fire, an effort was made to feed the gas in against the ventilating pressure of the fans. Obviously, this would not work, and then a hose was used in order to get enough pressure to counteract the fan action. Although the fire was extinguished, the resultant effect of fire and the high pressure water was that new insulation was required.

Regulation and Short Circuit Characteristics

It has been known for many years to designers, that alternating current generators can give, at the instant of short circuit, a much greater current than that which they will give on continued short circuit. The first emphatic evidence of this, in the writer's experience, was in connection with the first Niagara generators in 1894. Upon short circuiting one of these machines at full speed and normal voltage, the results indicated a current rush so great that it was apparent that it was limited only by the armature self-induction, and not by the so-called synchronous reactance. Later, after being put into actual commercial service, it was found necessary to brace the end windings on these machines. However, at that time, no suitable instrument, such as the oscillograph, was available for determining the conditions on short circuit, and the phenomena did not permit of much experimental investigation.

Similar evidence was found from time to time, as in the first Manhattan Elevated engine type generators, which bent their end windings out of shape on a dead short circuit. But the real possibilities for trouble in this matter did not develop until the large capacity turbo-generators came into use. In these machines, the armature ampere turns per pole are so high, compared with moderate speed alternators, that the stresses due to the stray magnetic fields on short circuit are much greater

than the natural rigidity of the end windings will withstand. The manufacturer of such apparatus, without data of any quantitative value at hand, did not fully recognize the real weakness in the end windings until disaster overtook them. Even then it was a long and difficult undertaking to overcome the trouble. All kinds of designs of end supports, and various arrangements of end windings were tried, with more or less success. But each new step in the increase in capacity opened up the problem again. It was soon noted that those armature windings which were made up of cable or small wires, suffered most on short circuit, and for awhile there was a tendency on the part of some manufacturers to use heavy, solid conductors to give rigidity in the end windings. This was effective within certain limits, but was very expensive from the design standpoint, as on account of eddy currents in the buried copper It was necessary to work at a very low current density, which was not economical in winding space.

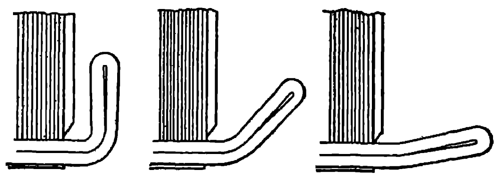


FIG. 20

In this country, the types of armature windings finally narrowed down to the open-slot construction, usually with an upper and lower coil per slot, with the end winding arranged in two layers, similar to d-c. armature windings, or the common induction motor primary windings. This turbo end winding was extended at various angles to the axis of the machine from almost parallel up to 90 deg., as shown in Fig. 20. The principal survivor of these types, is one which extends at some angle between 30 and 60 deg. to the axis. There are several reasons for this,—first, it allows a very substantial bracing to be applied to the end windings. Second, the stray fields around the end windings do not, to any extent, cut the adjacent solid parts, such as the end housings, stator and end-plates, etc. An angular position of approximately 45 deg. seems to be a good compromise on these points. Ample supports, as shown in Fig. 21 can be applied for bracing the windings against movement in any

direction. Such end windings are usually braced against metal supports attached to the stator end-plates. The coils are so clamped to the racks, and are so braced against each other that the windings will sustain a dead short circuit across the terminals, even in the largest capacity machines, without injury.

On some recent large turbo-generators the end windings have been further strengthened by double metal racks between the two layers of windings, so arranged as to securely key these two layers to one another at certain points. Moulded mica troughs are placed around the coils as an extra insulation from the metal racks. By this keying of the two layers to one another, the winding as a whole is stiffened, quite irrespective of any other clamping arrangement. In fact, this is practically equivalent to putting the end windings in rigidly held slots, thus approaching the conditions which obtain in the buried part of the coil.

In order to limit the momentary short circuit current, the armature reactance is now usually made as large as the condition of the design will permit. This naturally means high ampere turns per pole, which in turn means high synchronous reactance, and consequently poor inherent regulation of the machine, especially on inductive loads. This can be illustrated by the following example: Assume a 5000-kw. unit of an earlier design, which can give 25 times full load current on momentary short circuit. By certain improvements in the design of the armature coils, such as the use of deeper slots, better subdivision of the copper to eliminate eddy currents, improved ventilation and conduction of heat, etc., the capacity of the machine is assumed to be increased to 10,000 kv-a., the number of armature turns remaining the same as before. It is evident that when short circuited, the revised machine will give the same total current as on the former rating, which, however, is only 12½ times the rated current on the new capacity basis. Obviously, the end winding stresses are no greater than before, although the nominal capacity has been doubled, and if it were possible to satisfactorily brace the end windings with the former rating, the same bracing should be effective on the new rating. This illustrates, roughly, what is taking place in later designs, although the steps in the change may not be just those mentioned. Again, in the above example, it is obvious that, with the now rating, the inherent regulation at full load is the same as at 100 per cent overload on the old rating, which means that it is relatively poor. Another way to express this is, that the old rating might

give $2\frac{1}{2}$ times full load current on steady short circuit, while the new rating gives $1\frac{1}{4}$ times.

This condition of poorer regulation is inherent in the newer practise, but is apparently acceptable to the users of such apparatus, for a variety of reasons which do not come within the province of this paper.

Conclusion

The foregoing covers, in a general way, many of the problems encountered in large turbo-generators, and defines the situation as it stands at present.

It may be suggested, in connection with the temperature problem, that the high temperatures obtained are due to forcing the construction too far; but, in answer, it may be stated that it is forced no further in this feature than in many others. The whole design has been carried far beyond the most economical construction, from the generator standpoint alone. In fact, the whole machine is more or less a compromise between desirable conditions as a generator, and most economical conditions as part of a combined turbine and generator unit. It may be added that the ultimate limits in construction and capacity will be obtained only when the steam turbine conditions are satisfied, and there are indications that possibly this result is being approached now with the present high speeds.

There is one small consolation in all the confusion of development which has attended the turbo-generator work, in the few years it has been with us, namely, the question of choice of speed has been practically eliminated. For 25 cycles, there remains only one speed, namely 1500 revolutions, with two poles, from the smallest unit up to 25,000 kv-a. as a possible upper limit. For 60 cycles, up to 5000 kv-a , two-pole machines at 3600 revolutions are being furnished, while from this capacity up to 20,000 kv-a. four poles may be used.

It will be evident to any reader of this paper, that the designers of large turbo-alternators have had a strenuous time during the past few years—very much more so than is indicated herein, for their successes, rather than their failures have been discussed. In fact, much of the time they have been working ahead of their data and experience. In presenting this situation from the design point of view, it is hoped that a better and clearer understanding of the turbo-generator problem will be obtained by all who are interested in such apparatus.

TEMPERATURE AND ELECTRICAL INSULATION

FOREWORD—In 1911 and 1912, a revision of the standardization rules of the American Institute of Electrical Engineers was being made. The problem of temperature guarantees was referred to a sub-committee, consisting of Dr. Steinmetz and Mr. Lamme. It was decided by the Standards Committee to hold a mid-winter convention of the Institute in February, 1913. In order to furnish a basis for discussion of the temperature problem at this convention, the sub-committee on temperature collaborated in the preparation of this paper.

It may be noted that later information has modified some of the figures for temperature limits.—(ED.)

THE problem of permissible temperature limits in electric apparatus is largely that of the durability of the insulation used. As this may consist of materials of widely varying heat-resisting qualities, the probem resolves itself into one of consideration of the properties of the materials themselves.

The durability of insulation may be considered from two standpoints, the mechanical and the electrical. Temperatures which may ruin the insulation, from a mechanical standpoint, may not radically effect its dielectric strength. This is particularly true with moderate voltages where the insulation serves largely as a separating medium. The purpose of the insulation usually is two-fold: First, it must serve to separate, mechanically, the electric conductors from each other, and from other conducting structures, and second, it must withstand the voltage between the electric conductors and between the electric circuits, and other conducting parts. In lower voltage apparatus, usually only the former function applies, as the mechanical separation is more than sufficient to withstand the voltage used. The dielectric strength of the material is, however, of first importance in high voltage apparatus.

A great majority of the electrical "breakdowns" on low voltage apparatus is due to mechanical weaknesses, as far as the temperature problem is concerned; that is, high temperatures may make the insulation brittle, or crisp, so that it may flake off, or powder, or crack, or be crushed by mechanical action, thus allowing the conductors to make contact with each other or with adjacent conducting material.

The "life of insulation" is an indefinite term and must be defined in time, mechanical strength, absence of foreign materials of a conducting nature, etc. Almost all insulating materials will be somewhat affected in time, and many of them tend to become dry and brittle. The rate at which deterioration occurs with any given material, is some complex function of the temperature and of other conditions.

Classes of Insulations

Insulations may be classified under three headings, depending upon their heat-resisting properties. However, all such classifications must be relative, for no absolute limit can be fixed, as there is no definite point at which injury or destruction can be said to take place.

The usual insulating materials can be considered as included in three general classes:

Class A. This includes most of the fibrous materials, as paper, cotton, etc., most of the natural oil resins and gums, etc. As a rule, such materials become dry and brittle, or lose their fibrous strength under long continued moderately high temperature, or under very high temperature for a short time.

Class B. This includes what may be designated as heat-resisting materials, which consist of mica, asbestos, or equivalent refractory materials, frequently used in combination with other supporting or binding materials, the deterioration of which, by heat, will not interfere with the insulating properties of the final product. However, where such supporting or binding materials are in such quantity, or of such nature, that their deterioration by heat will greatly impair the final product, the material should be considered as belonging to class A

Class C. This is represented by fireproof, or heat-proof materials, such as mica, so assembled that very high temperatures do not produce rapid deterioration. Such materials are used in rheostats and in the heating elements of heating appliances, etc

All the above are relative terms. The first class, for instance, represents materials which are really more or less heat-resisting, but which deteriorate at lower temperatures than those in the second class, which are defined as heat-resisting. Also, the fireproof materials of the third class are not strictly heat-proof or fireproof, but will simply withstand very high temperatures for relatively long periods without undue deterioration

In class A, the materials appear to have a very long life (or an almost indefinitely long life, aside from mechanical conditions) if subjected to ultimate temperatures which never exceed 90 deg. cent. Also, they appear to have a comparatively long life, even at ultimate temperatures as high as 100 deg. cent. At materially higher temperatures than 100-deg. cent., the life is very greatly shortened, and temperatures of 125 deg. cent. will apparently ruin the insulation, from a mechanical standpoint, in possibly a few weeks, if such temperature is maintained steadily However, for low voltages, the insulating qualities may still be very satisfactory, even at this temperature, and therefore the destruction of the insulation is purely one of injury or breakdown from the mechanical standpoint, as stated before. Tempera-

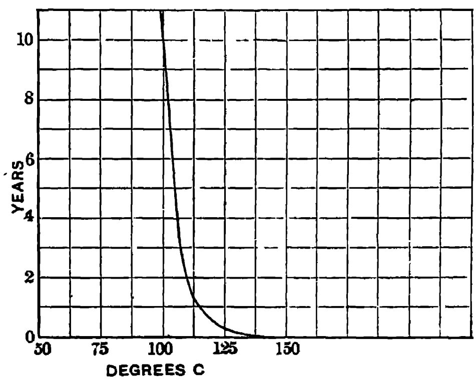


FIG. 1

tures as high as 160 deg. cent. on such insulations for a considerable period may not entirely destroy their insulating qualities, although, mechanically, such temperatures appear to be impracticable, except for very short periods.

In order to illustrate the relation between the possible life and temperature of class A insulation, Fig. 1 is shown. This must not be taken as representing actual results, but is simply intended to illustrate, in a very approximate manner, the very great shortening of the life of insulation by increase in temperature.

It may be assumed that at very high temperatures, the insulation will have practically the same life, in actual hours of high temperature operation, whether the temperature is applied continuously or intermittently. For example, if an insulation has 10,000 hours life with a certain high temperature continuously

applied, it is assumed that it will also stand the same temperature for 10,000 hours in short periods, provided the intermediate temperatures are low enough to represent an indefinitely long life. It is probable that under the intermittent condition, the life will really be slightly greater, due to the fact that depreciation will be largely mechanical, and the insulation may "recover," in some of its mechanical characteristics after each period of high heating.

If, therefore, high temperatures are reached intermittently, with intermediate periods of lower value but still high enough to shorten the life of the insulation, it may be assumed that the total life of the insulation is the resultant of the life under the two temperature conditions.

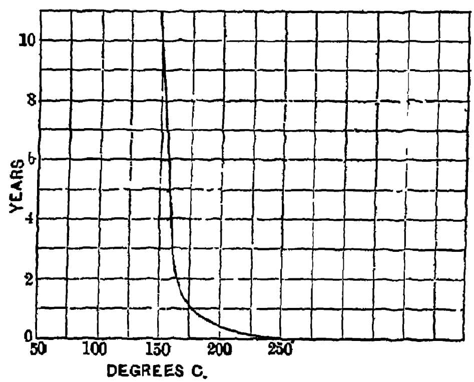


FIG. 2

In heat-resisting materials, such as those of class B temperatures of 125 deg cent are comparable with 85 deg. cent or 90 deg cent in class A, and 150 deg cent in the former is comparable with 100 deg. cent in the latter Fig 2 illustrates very approximately the life-temperature curve of such insulations As in Fig 1, this should not be taken as an exact representation of the actual life Due to the greater heat-resisting qualities of such materials, it appears that relatively higher temperatures are not as quickly harmful as in the first class

In class C materials, it is difficult to give any reasonable indication as to the limits of temperature, except that very high temperatures, (practically up to the point of incandescence) are found in some heating appliances.

Temperatures and Flow of Heat

As the insulation, in itself, is not usually the seat of generation of loss or heat, it is the temperature of adjacent materials which must be considered in defining the conditions in the insulation. The temperatures of the adjacent materials should therefore be considered only in so far as they affect the insulation itself, and where such temperatures do not affect the insulation, or the life of the apparatus, or its normal perfomance, they are immaterial

Considering the influence of the temperatures of the adjacent media, the direction and amount of heat flow must be taken into account, as the maximum temperature in the insulation is dependent upon these. In the case of armature windings, for instance, the heat flow may be from the buried portion of the

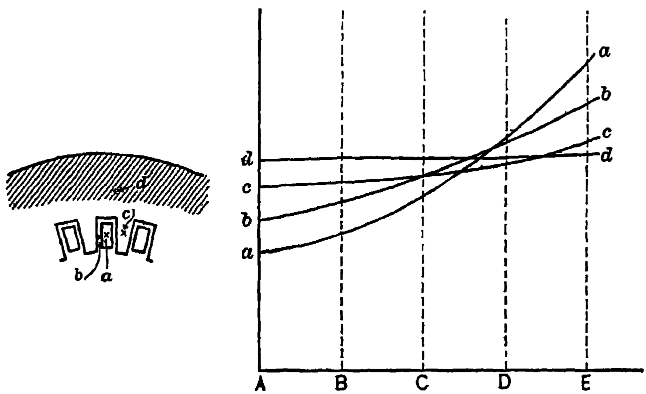


Fig. 3

coils toward the end windings. It also may be from the buried copper through the insulation to the armature teeth, or there may be a reverse heat flow from the iron to the copper, depending upon the various factors of construction, heat conductivity of the materials, amount of heat generated in the various parts, ventilation, heat dissipation etc.

Depending upon conditions of heat flow and distribution, various methods of temperature determination may be used. No method is accurate, unless all the conditions of heat flow are accurately known, which is never the case in commercial machines.

The difficulties in the problem of commercial temperature determination are illustrated by Fig. 3.

In the figure, *a* represents the temperature inside an armature coil, *b* the temperature between the insulation and the iron of an armature tooth, *c* that in the body of the tooth, and *d* that in the body of the core at some point back of the coils and teeth. Let the temperatures at no load be represented on the ordinate *A*. Then, at some load, represented by ordinate *B*, the relations of the various temperatures have changed. At *C*, *D* and *E*, there are still greater changes, depending upon the heat generation and distribution. If the rated capacity of the machine is at *E*, for instance, then the armature copper is hotter than the iron, while if rated at *B*, the reverse would be true. Obviously, no rule can be formulated to cover these various conditions in different machines, nor even in a given machine, unless all the heat generation, distribution, and dissipation characteristics are known. Obviously, as far as the insulation is concerned, the temperatures of *a* and *b* are the only ones which need be considered.

All temperature determinations of a commercial nature, are necessarily approximations, or relative indications, upon which proper margins must be allowed for the ultimate temperature possibly attained. Therefore, in apparatus where there are liable to be discrepancies of 10 deg. between the measurable and the actual ultimate temperatures, a limit of 90 deg cent. should be allowed by conventional temperature measurement on insulations in which 100 deg. is set as the maximum temperature with a reasonable length of life.

The conventional methods of temperature measurement, as by resistance, and by thermometer, do not usually give the maximum temperature, but give either the average, or the outside surface, values, and, when measuring the temperature by these methods, which are the only ones generally applicable, an allowance must be made in windings for possible local higher temperatures. These methods apply especially to those machines of moderate or low voltages in which the insulation is relatively thin, so that the heat gradient from the inside copper to the outside surface is small. Also, they apply particularly to those machines in which the conditions of ventilation are not normally difficult, and in which a fairly thorough distribution and dissipation of heat occurs among the various parts, such as in ordinary direct-current armatures, induction motors primaries. stators and rotors of moderate speed alternators in which the width is relatively small compared with the diameter, etc

As the ultimate temperatures obtained by the apparatus depend upon its rise above the room temperature, or that of the cooling medium, and as such temperatures may vary over a wide range, it is not practicable to specify or guarantee ultimate temperature of apparatus without also specifying the elements upon which it depends This, therefore, results in specifying the temperature rise in relation to that of the cooling medium.

While most apparatus operates at materially lower cooling temperature than 35 deg. cent. to 40 deg cent., yet such temperatures are sometimes reached for considerable periods of time in steam stations, and it appears therefore as justifiable to choose the permissible temperature rise, such that, at room temperature of 35 deg. cent. to 40 deg. cent , an ultimate temperature of 85 deg. cent to 90 deg. cent. by conventional methods of measurement, is not exceeded This means, therefore, a temperature rise of 50 deg. cent. with conventional methods of testing, such as by increase of resistance, or by thermometer, in those insulations which can stand a continuous ultimate temperature of 100 deg cent with a comparatively long life. This allows an excess of 10 deg. cent. to 15 deg. cent. for local spots, or for the temperature gradient through the insulation. A less allowance should be made for this difference when methods of temperature measurement other than the conventional are used, and which approach more closely to the highest temperature actually attained

When the above temperatures are liable to be materially exceeded for long periods, heat-resisting insulation of class B is recommended With such materials, a temperature of 125 deg. cent is comparable with 85 deg cent to 90 deg. cent. in the materials of class A Therefore, on this basis of a room temperature at 40 deg cent or 45 deg cent., rises of 85 deg. cent or 80 deg cent should not be considered harmful However, in those special cases where the conventional methods may not sufficiently approximate local high temperatures, as may be the case in large turbo-generators, or in wide core alternators of large capacity, the rises of 80 deg cent. or 85 deg cent should not be specified by resistance or thermometer, but preferably some lower temperature such as 50 deg cent thus allowing a very considerable margin for local higher temperatures In such apparatus with the higher temperatures, which require class B insulation, there is liable to be less uniformity of heat distribution

If special methods of temperature measurement, such as exploring coils or thermo-couples are used in such apparatus, the temperature limit of 125 deg cent. should be considered, and not the conventional 50 deg cent rise. In those machines of this class which have relatively thick insulation, and consequently may have a high heat gradient between the copper and the iron, (depending upon how much heat is flowing from the copper to the iron) an ultimate temperature of the inside insulation of 150 deg cent is considered as the limit, this being comparable with 100 deg. cent with insulations of class A.

In certain classes of apparatus which are artificially cooled by air from outside the room, the cooling is accomplished partly by dissipating heat to the artificial air supply, and partly by dissipation into the surrounding room. If the temperatures of the cooling air and of the room are widely different, the resultant of the two temperatures should really be taken as that of the cooling medium.

The variation of the temperature rise has heretofore been considered as having a definite relation to the temperature of the cooling medium. However, it appears that it does not follow any definite simple law, but it is sometimes positive and sometimes negative, so that no satisfactory correction for room temperature is possible at present. It is therefore desirable to make the temperature tests at a room temperature as nearly as possible to some specified reference temperature, so as to make any temperature correction negligible The reference temperature in the guarantees should therefore be such as can easily be secured; that is, it should be the average temperature of the places at which the apparatus may be operated This is from 20 deg. cent to 25 deg. cent , and as it is easier to raise than to lower the room temperature, the upper figure is advisable as a reference value. This reference temperature therefore should be chosen as 25 deg cent., which is in accordance with the previous A I E E standard.

Measurement of Temperature

In the conventional methods of temperature measurement, by thermometer, and by resistance, many conditions should be taken into account, and good judgment is required, in all cases, or fallacious conclusions may be obtained

There are many conditions which affect both the accuracy of the resistance and the thermometer methods of measuring temperature The resistance method measures only the average

temperature rise, and not that of local hot spots. However, it measures the internal temperature of windings, and therefore no correction is required for the temperature gradient through the outside insulation The proposed margin between the result by the conventional method, and the actual temperature can therefore be allowed, in the resistance measurement, as the difference between the warmer and the average temperatures in the windings. In the resistance method of measurements, the rate of transfer of heat from one part of the winding to another will not greatly affect the result, as the measurement indicates an average temperature, which is that obtained if the heat were equalized throughout the winding. However, the rate of flow of heat from the windings through the outer insulation to other parts, will affect the temperature measurement by resistance, and preferably the measurement by this method should be taken during operation in those parts where this is practicable, as in field coils, and some other instances. In those parts where the resistance cannot be measured during operation, this should be done as quickly as possible after shut-down, and the time taken to shut down the apparatus should not be unduly long. Preferably, during shut-down of rotating apparatus the normal current should be maintained on the apparatus until at least a relatively low speed is obtained. This would represent only an average condition, as the ventilation at lower speed is very greatly decreased, while the losses in the windings will remain normal, thus tending to give an increased temperature in the windings. It would be difficult to fix any definite rule which would give the exact temperature conditions during shut-down.

In the measurement of temperature by thermometer, considerable judgment is required Wherever possible, the temperature should be taken during operation, but the thermometer with its pad should be so placed that it does not interfere with the normal air circulation. In thermometer readings, as usually obtained on windings, the heat gradient through the insulation must usually be allowed for, this being 10 deg. to 15 deg as previously defined However, depending upon the method of taking the temperatures, this allowance should vary over a considerable range, depending upon whether or not the method of measurement approximates the actual internal temperature For instance, the total heat gradient from the inside copper to the outside air will be that through the coil insulation, plus the thick covering pad over the temperature bulb If the gradient

through the covering pad is very large compared with that through the insulation, the thermometer may indicate almost exactly the internal temperature of the copper; that is, the heat gradient through the insulation to the thermometer, may be relatively small compared with the total gradient to the air. This is particularly true where the thermometer rests on a metallic seat which covers a considerable portion of the coil surface. In this case, the heat which affects the thermometer bulb will pass through a relatively large section of surface, with a correspondingly small drop in temperature, so that the bulb more closely approximates the temperature of the inside copper.

Where there is local heating in the windings, and a consequent liability of rapid transference of heat to other parts, the results obtained by the thermometer method will vary to some extent with the rapidity with which the actual measurement is made; that is, the more quickly the thermometer can be brought up to the full temperature, the more accurately the temperature of the hottest part is determined. With a very rapid method of measurement, it may be possible to measure practically the internal temperature of the copper of the winding before any great heat transference or dissipation has occurred. In such cases, obviously, the full allowance for the usual temperature margin should not hold. It should be fully understood that it is the ultimate temperature, and not the temperature rise, which should be considered as the limiting condition, and that the measured rise, plus the allowances for temperature gradient, plus the measured room temperature, is simply an indication of the possible ultimate temperature. By whatever method the temperature measurement is made, in all cases the results may be considered as more or less approximate, and in the end, it is the manufacturer who must supply the necessary margin over the approximate measurement, in order to make the machine safe.

A blind adherence to some particular rule or method of taking temperatures, may lead to fallacious results in some instances. In armature windings, in particular, incorrect readings may be obtained after shut-down. For example, if the armature iron back of the armature teeth were hotter than the armature teeth and coils during operation, then the temperature to which the insulation is subject during operation may be considerably lower than that in the hottest part of the machine, due to the ventilation conditions when running. However, upon shut-down, the

temperature at the insulation may rise to that of the hottest part of the machine, and therefore a false temperature, by any method of measurement, might be indicated.

Recommendations

That with class A insulation, 90 deg. cent. be taken as the ultimate temperature limit, as indicated by conventional methods of measurement, or those which give similar results, and that 100 deg. cent. be considered as the maximum ultimate temperature permissible in the insulation, where a comparatively long life is a requirement.

That 40 deg. cent. be taken as the limiting temperature of the cooling medium, or room, and that, therefore, 50 deg. cent. be the permissible rise by conventional methods of measurement, with class A insulation.

That 25 deg. cent. be taken as the reference air temperature. With the permissible 50 deg. cent rise, this gives 75 deg. cent. as the average operating condition, by conventional methods of measurement, or 85 deg cent. actual temperature, when the usual margin represented by the temperature gradient is added.

An exception to the rise of 50 deg. cent. can be made in those cases where space or weight limitations are such that higher temperatures, with consequent reduced life, are commercially economical, such as in railway motors. In such cases, with class A insulation, a rise of 65 deg. cent. with reference air at 25 deg cent. is at present accepted as good practice.

With class B insulations, 125 deg cent be taken as the ultimat temperature limit, as indicated by conventional methods of measurement, or by equivalent methods, and 150 deg. cent. be considered as the maximum ultimate temperature permissible in the insulation It follows therefore that 80 deg cent. to 85 deg. cent. rise is allowable, with such insulations, by the usual methods of measurement

No temperature correction should be made for variation of the cooling temperatures from the reference temperature of 25 deg. cent

When the method of temperature measurement shows the highest temperature actually obtained in the insulation, the maximum temperatures specified for the given type of insulation should hold.

In the final decision on questions of temperature rise, the ultimate temperature should be the basis, rather than the rise.

TEMPERATURE DISTRIBUTION IN ELECTRICAL MACHINERY

FOREWORD—This paper was presented at the Chicago Section meeting of the American Institute of Electrical Engineers, November 27, 1916. A number of papers by the author dealing with the temperature problem had appeared before, but the purpose of this paper was to put the subject in more definite shape and bring it more nearly up to date. During the discussion of the paper, considerable new data was presented by the author, and it has, therefore, been included in this reprint.

This paper was listed for a second presentation before a regular meeting of the Institute at Schenectady in April, 1917, with a view to obtaining a further discussion, particularly by engineers on design work. This meeting was cancelled due to the declaration of war.—(Ed.)

THE laws governing heat flow and temperature distribution are so similar, in many respects, to those governing electric current flow and electric potentials, that it is rather surprising that the former have received so little attention in comparison with the latter. Some of the laws of heat flow are so well recognized that their application to the problem of temperature distribution in electric apparatus should have been a leading feature in the early developments in such apparatus; whereas, on the contrary, it is only recently that very careful study has been made of such application.

One object of this paper is to indicate, in a comparatively simple manner, some of the conditions which fix the temperatures in different parts of electric apparatus. The explanations given cannot be considered as new or novel in substance, but are merely the application of fairly well known principles of temperature and heat flow to electrical machinery. Before going into the general problem, certain simple conditions may be stated, such as:

1. The heat flow between two points is proportional to their temperature difference and to the heat resistance of the path or paths between them. Note the resemblance to Ohm's law.

As a corollary to the above, it should be evident that between

two points at the same temperature, there should be no flow of heat.

2. The total temperature drop between any two points or media of different temperatures will be the same through all paths of heat flow.

3. There are no true non-conductors of heat, and, conversely, no perfect conductors.

4 Heat conduction and electric conduction bear some quantitative relation to each other, in the broad sense that all electric insulators are relatively poor heat conductors, while good electric conductors are correspondingly good heat conductors. There is apparently no rigid relation between the heat resistance and electric resistance of the various materials used in electric machinery, but the general relation holds and there are apparently no radical exceptions

5 The rise in temperature at any point, due to generation of heat, is dependent (a) upon the total heat generated, and (b) upon the amount of heat which can be carried away along all available paths per degree of temperature difference. The temperature will rise until the heat dissipation equals the heat generation

6 There are two ways to lessen the heat flow along any path. (a) By interposing higher heat resisting materials. (b) By lessening the temperature difference, as by raising the temperature of the part through which the heat is to be conducted. Conversely, the heat flow can be increased along any path by the use of better heat conducting materials, or by paths of lower heat resistance, and by lessening the temperature of any part to which the heat is to flow.

What makes the problem unduly complicated, in electrical machinery, is the fact that there are several different sources of heat generation, which may be, and often are, all active at the same time. Moreover, the heat losses may be distributed through the various heat conducting paths in such a way as to render any calculation very difficult and more or less inexact, except in a general way. For example, there is heat generated by losses in the copper conductors, obeying one law; while there is heat generated in the iron parts under a quite different law, and there may be heat generated by windage and friction, according to a third law. As these different losses may act in different parts of the heat conducting circuit, it should be evident that the problem of determining the exact heat distributions,

and the temperature, is a very complex one. Such a determination is in the province of the expert analytical designer of such apparatus, but certain general conditions are of interest to all users of electric apparatus.

Consider first the general conditions of heat dissipation from an armature coil In Fig. 1 is represented an armature slot with the surrounding iron, and with two separate "coils" per slot, as is now the most common practise. Let it be assumed that the point *a* represents the "hot spot", or part at highest temperature in the apparatus. The heat from this part can flow along two general paths, namely, longitudinally through the copper conductor itself to the end windings, and thence to the air, and

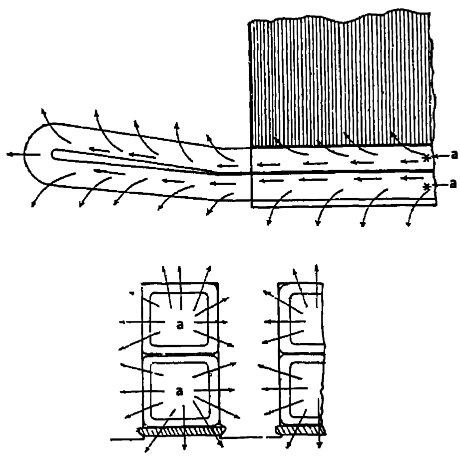


FIG. 1

laterally through the insulation to the surrounding iron, or to the ventilating ducts. From the iron the heat flow is then through various paths to the external cooling air.

LONGITUDINAL HEAT FLOW

Considering first the longitudinal conduction of heat in the coil, then starting at the point *a*, the first unit of length conductor will have a certain loss. If the heat generated by this first unit loss were all that need be considered, then the drop in temperature, from the point *a* to the end windings, would be simply a function of the heat-conducting properties of the conductor itself. But the next unit length is also generating its

own unit loss, so that the heat flow from the second to the third unit length is due to two units loss; in the same way, the flow to the fourth unit length will be due to three units loss, etc Therefore, the temperature drop, or temperature difference per unit length of conductor, increases more rapidly as the point *a* is departed from, and if it is at a considerable distance from the end winding, and the losses per unit length are comparatively high, a very high temperature may be required at *a* to conduct all the heat longitudinally to the end windings. In very wide core machines the longitudinal drop may be so great that the temperature at *a* in practise will be so far above that of the surrounding iron, that a very large percentage of the actual heat is conducted laterally through the insulation to the iron, even if the iron is at a comparatively high temperature. However, in narrow cores, the drop to the end windings may be, in some cases, so very low, possibly 5 to 10 degrees, that with good heat dissipation from the end windings themselves, the point *a* may have, for instance, an actual temperature of 40 deg. cent. If the iron next to *a* also has a temperature of 40 deg. cent. then there would be no flow of heat from *a* to the iron. Furthermore, in such a case, as the iron temperature over the whole width of the core may be fairly uniform, and as the copper temperature decreases from *a* to the end windings, obviously as we depart from the point *a*, there would be heat flow from the iron to the copper, and thus the windings would tend to cool the core. This is frequently the case with light loads on a machine, for in such conditions the coil loss is low, while the iron loss remains fairly constant for all loads In such case there may be heat flow from the iron to the copper along the whole length of the buried portion of the coil At some higher load, the copper loss varying as the square of the load, the increased longitudinal drop will bring the copper temperature above that of the iron so that the heat flow is from copper to iron. This condition is illustrated by Fig 2

It must be recognized that the lateral flow of heat, from the coil to the iron, reduces the longitudinal drop, such reduction depending upon the relative percentages of heat flow along the two paths. It must also be borne in mind that in order to have such longitudinal heat flow, the end windings must be able to dissipate their own heat at lower temperature than would be attained at *a*, or in the core If the end windings have little or no ventilation, or heat dissipating capacity, then their own

generated heat may bring their temperatures higher than those of the armature iron so that the heat flow actually may be from the end windings toward a, and then laterally through the insulation to the core In such case, the hottest spot will be in the end winding rather than in the buried part of the coil Obviously when such condition occurs there is no possibility of either the end windings or the buried part of the coil being cooler than the iron, for the heat flow throughout is toward the iron

Lateral Heat Flow

Considering next the lateral flow of heat through the insulation to the iron, the amount of heat conducted is a function of the temperature difference and the resistance of the conducting path. Or, in other words, if a given amount of heat is to be conducted through a path of given resistance, the temperature in the heat generating part will rise until the required heat is conducted away

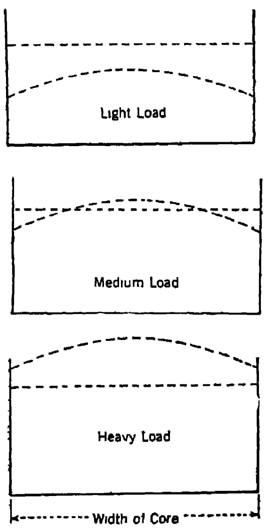


Fig. 2

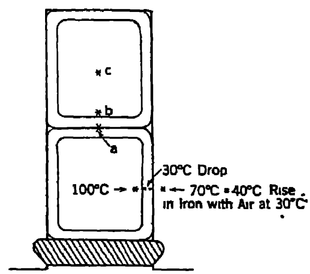


Fig. 3

To illustrate this problem more concretely, let Fig. 3 represent the temperature conditions in a section of an armature Assuming, for example, the temperature of the copper inside the coil insulation as 100 deg cent., the iron temperature as 70 deg. cent., and the air temperature as 30 deg cent., then the following conclusions may be drawn.

(a) From the outer coil (the one next to the air gap) through the wedge to the air gap, the temperature drop will be 100 — 30 = 70 deg. cent. Obviously, any temperature measurement made outside the wedge, next to the air, will approximate the

temperature of the air and not of the copper Any temperature measurement made beneath the supporting wedge will measure some intermediate temperature between the copper and the air If the temperature drop through the wedge should be equal to that through the insulation, then a measurement underneath the wedge should show half the temperature drop through insulation and wedge, and obviously, the measured temperature would be far below that of the copper.

(b) If the temperature is measured at the outside of the coil, between the iron and the insulation, it would approximate the average of the temperatures of the iron and of the outside insulation, or practically the temperature of the iron If the iron should be at different temperatures at the sides of the slot and at the bottom, then obviously different readings would be obtained, depending upon the location of the measuring device. It is evident that such temperature measurements give no indication whatever as to the true internal temperatures of the coil, for the heat flow and the resistance of the insulation are nowise involved in the measurement.

(c) At a point *a*, between the two coils, there should be but little heat flow through the insulation, unless the copper is comparatively narrow. If there is but little heat flow through the insulation at this point, then eventually the temperature at the point *a* must rise to approximately that of the copper in the two coils. Therefore, a measuring device located at *a* will approximate the temperature of the copper itself, and is, in general, a good indication of the hot spot at that part of the winding Therefore, as a practical method of temperature determination, a thermo-couple located at *a* is about the most satisfactory device that we have. However, the location of the point *a* along the slot is also of importance on account of the longitudinal flow of heat in the conductor and the consequent temperature drop In other words, the direction of heat flow in the coil itself, must be taken into account Therefore, a thermo-couple located as above, is only satisfactory when the general location of the hot spot is known beforehand This is usually determined, in a general way, for a given type or line of machines, by locating several thermo-couples along the slots

With narrow slots and comparatively thin conductors, and especially with very heavy insulation, there is some flow of heat through the insulation which lies between the two coils, this heat passing out sidewise to the iron In such case, the point *a*

may be of somewhat lower temperature than the copper. It may happen also, in some cases, that, due to unequal losses and heating of the two coils in the same slot, one is at a higher temperature than the other In such case, due to the heat flow between the coils, the temperature indication at *a* will not show better than an average of the two temperatures Furthermore, if the temperature at *c*, in a coil subdivided into many insulated conductors, is materially higher than at *b*, then the temperature indication at *a* may not be a close approximation to the maximum temperature

FLOW THROUGH IRON PARTS

In the ordinary armature, after the heat passes from the copper to the iron, there is still quite a problem involved in the dissipation to the surrounding medium, which is usually the air The direction of the heat flow to the iron will depend, to a considerable extent, upon the arrangement and location of the heat dissipating surfaces There are two general paths of heat conduction in all armature cores; namely, a flow along the laminations to where their edges come in contact with the air or with other material, and a flow across the laminations toward heat dissipating surfaces The flow along the laminations may be calculated with fair accuracy. Across them it is difficult to determine such flow, largely because the laminations are insulated from each other by materials which are poor conductors of heat Also such flow is affected not only by the insulation between laminations, but by the perfection of contact In other words, the heat flow may be affected by pressure. According to the various figures available, the heat flow per unit volume of material along the laminations is from ten to one hundred times as great, for a given temperature difference, as across them Obviously, therefore, heat dissipation from the iron by flow across the laminations should be considered relatively inefficient, yet in the vast majority of rotating machines the heat dissipation is largely across the laminations. The reason for this is that by placing ventilating passages or ducts, parallel with the laminations, at frequent intervals in the core, the cross section of the heat path in the intervening iron sections, may be made very large compared with the heat to be dissipated, so that the density of flow is very low By the same procedure the length of the heat path is made quite short Thus in practice, the temperature drop through the laminations themselves may be made relatively small compared with other drops However,

not all the heat in the iron passes across the laminations to the ventilating ducts, for where the length of the path, along the laminations to any heat dissipating surface, is not large, a very considerable amount of the heat may be dissipated from the edges of the laminations themselves. In fact, in certain types of machines with very shallow iron cores, experience has shown that the ventilating ducts, parallel with the laminations, may be omitted, provided good ventilation is obtained over the edges of the laminations. It is evident, therefore, that the flow of heat and distribution of temperature are dependent upon the arrangement of the iron, dimensions and location of the ventilating surfaces etc.

Heat Flow to the Air

After the heat has passed from the copper to the iron, the resultant of the copper and iron heats must be conducted to the cooling medium, which is usually the surrounding air In the case of air, there is usually a considerable drop in temperature from the solid surface to the cooling air itself, the amount of such drop depending upon the ventilating conditions. In practise, there appears to be a film or layer of air which adheres very closely to the solid surfaces. This forms a sort of heat insulating film, retarding the flow of heat to the cooling air In air ventilation, the effect of any considerable air movement over the surface appears to be that of scouring this hot film away from the surface and *replacing it with a film of cooler air* Merely scouring or rubbing the hot film away from the surface is not particularly advantageous unless some means is furnished at the same time for supplying an ample quantity of cooler air to take the place of the removed hot film. Rapid air circulation, by means of a supply of air from the outside, appears to accomplish both results in one operation. Thus, one of the principal actions of air ventilation appears to be that of scouring away the hot contact film, while a second action is to carry the hot air away without mixing it with the incoming cooler air Whatever portion of the dissipated heat is absorbed by the incoming cooling air adds that much to the temperature of the air itself and eventually to that of the apparatus to be cooled. Thus mixing the outgoing with the incoming air makes a sort of Siemens' regenerative furnace and the machine bocomes cumulatively hotter and hotter until the dissipation through other paths becomes equal to the heat generated. In such cases the ventilation

of the machine may only be useful in equalizing or redistributing the temperatures in the various parts.

From the preceding analysis, it would appear that the temperature at the hottest part of the coil is fixed principally by the heat flow through the copper, and its surrounding insulation, directly to the air, and by the flow from the copper to the iron, and from the iron to any exposed air surfaces, and then to the air. Along the first path, there are three principal temperature drops. namely, in the copper itself, then through the insulation, and then from the outside surface of the insulation to the air. Along the second path, there are also three temperature drops; namely, from the copper through the insulation to the iron, then from the iron to the exposed air surfaces, and then from the surfaces to the air. Along the first path each part of the copper path is generating its own heat, to be conducted away, in addition to that which is to be conducted from other parts of the path. In the second path, each part of the iron path may be generating its own heat, which adds to that coming from other parts. The relative amount of heat conducted along each path is dependent upon so many conditions, which vary with the load, that no one but an analytical designer backed by experience could even approximate the values by calculation. However, it should be obvious that any measuring device applied to the outside or cooling surface does not, and cannot, directly approximate the temperature of the hottest part, except in those rare cases where the hottest part is dissipating heat directly to the air. This is true only in very special cases such as series coils of bare strap, etc. In any coil or part of the apparatus which is heavily insulated, that is, which is covered by poor heat conducting materials, an external temperature measurement is an extremely poor indication of the true internal temperature, unless many other conditions are known which may give an indication of the internal temperature drops. In different types and constructions of rotating apparatus, hot spots may hold quite different relative positions with respect to the cores and windings, so that no reasonable rule can be made to cover all cases. Moreover, in some classes of apparatus, it is not practicable to make any temperature measurements until after the apparatus is shut down, and this introduces other very important errors which should be considered, such as cooling effects as a whole, during the period of shut-down, equalization of temperature due to internal conduction, etc.

EQUALIZATION OF TEMPERATURE, ETC.

When there are hot spots, or zones, or areas, of different temperatures, in an armature winding, for instance, such difference in temperature is maintained by the continual generation of heat in the various parts But the moment that such generation of heat is stopped there is immediately a tendency for equalization of temperatures by flow of the stored heat from the hotter parts to the cooler. In good heat conducting materials, as copper, such equalization may be very rapid, so that a temperature indicating instrument of a sluggish type may not indicate anything like the true maximum temperature of the spot where it is placed, if applied after the load is removed, especially if the rate of heating of the thermometer bulb is much less than the rate of heat transfer from one part of the winding to another If located on a hot spot, the reading may rise to some intermediate value and then drop off as the hot spot cools by heat conduction to other parts. If located upon a cool spot, it may rise slowly for a considerable period, due partly to sluggishness of the thermometer and partly to the cool spot rising in temperature by conduction of heat from some other part. The conditions are so varied that no reliable conclusions can be drawn, from the action of the thermometer alone, in regard to the coolest or hottest spot.

A second condition which tends to make such temperature measurements fallacious, lies in the cooling action in the interval between load removal and shut-down to take temperature measurements In apparatus which depends upon a high degree of artificial cooling, such cooling effect may be very considerable. This is particularly true of high speed machines which require considerable time to come to a standstill. It is, therefore, desirable in such machines to obtain all possible temperature readings at normal speed and with load In rotating field machines, this is, to a certain extent, practicable, but in most rotating armature machines, the armature temperatures usually are not attainable until the machine is brought to a standstill, and even then some error may result from sluggishness or delay in taking the readings. One method which has been proposed at times, for lessening the sluggishness, is to heat the thermometers up to practically the normal operating temperature of the part to be measured, while the machine is still carrying load. At the moment of shut-down the heated thermometer is applied. This, to a certain extent, removes the factor of sluggishness in the ther-

mometer itself, but is only a partial compensation It must be considered that the outside of the insulation is at lower temperature than the inside, and that, therefore, the body of the insulation itself must have its temperature increased by flow of heat from other parts.

Fallacies in Temperature Guarantees and Measurements

In the older methods of determining temperatures, it was assumed that the thermometer readings, obtained on a winding, for instance, was a true indication of the temperature of the winding as a whole The manufacturers of electrical apparatus long ago recognized the fallacy of this method, as they had found from bitter experience that there were liable to be hotter parts in the machine than any thermometer readings would indicate. They, therefore, designed machines with regard to the possible hot spot temperatures as encountered in service, rather than any temperature which the exposed parts of the machine would show Thus in designing a certain machine for safety at the hottest part, not infrequently the exposed parts of the winding would show, by thermometer, comparatively low temperatures, such as 25 deg. to 35 deg cent. rise. Therefore, as the observable temperature readings came so low it became the fashion to call for 35 deg. cent guarantees and, in many cases, the operating public lost sight of, or perhaps never knew, the real meaning of such low temperatures. Among the designers of electrical machinery, it was recognized that a temperature rise of 35 deg. cent in itself was absurdly low, but that the object in operating at such low temperature on a part which could be measured was simply to protect the machine in some inaccessible hotter part, where the temperature could not be measured. From the present viewpoint, it is astonishing what reliance has been placed upon temperature readings in the past. For example, if a 40 deg. cent machine showed 41 5 deg cent rise on test, it was unsafe, while if it showed 38.5 deg. cent. rise, it was good. We now recognize that neither of these temperatures have any controlling value, unless many other conditions are known To the experienced man they simply mean that compared with the other machines of similar constructions and characteristics, which have proved satisfactory in service, they are reasonably safe. To the designer they mean that when proper corrections have been made for the various internal temperature drops, the highest temperature attained, at any point, will be within the limits of

durability of the insulating material used. The whole problem is a good deal like that of a determination of the voltage generated in a given power-house, by measuring the voltage at the end of a transmission-line. If we know all the constants of the line, and know the current flowing, etc., we can figure back to the generated voltage. Otherwise the voltage at the end of the line means but little. However, we know that if the system is designed with reasonable regard to economy in general, there may be from ten to twenty per cent. voltage drop from power-house to the end of the line. Therefore, by adding an approximate correcting factor to this voltage, we can make a reasonable estimate of the generated voltage. In the same way in electrical apparatus of certain types, a reasonable internal temperature drop may be approximated, which added to the observable temperature, gives a fair approximation to the hottest part, but *the result is an approximation and must be recognized as such.* Primarily, the manufacturer must make a safe machine for a specified service regardless of the temperature guarantees, and the temperature measurements made on most classes of apparatus should be considered simply as rough approximations to indicate that the manufacturer has made a reasonable attempt at a safe machine. This may seem a rather bald statement, but nevertheless it is a fair statement of the case.

Errors in Temperature Measurement

It has been shown in the preceding that the usual observable temperatures are in most cases only crude approximations to the real temperature conditions. It may now be shown that even the observable temperatures, obtained by the usual means, are in themselves only crude approximations in many cases. Take, for instance, the determination of temperature by increase in resistance; when the coil is heated its temperature may not be, and very frequently is not uniform throughout the coil. As an extreme example, if one-fifth of the coil length has a temperature of 80 deg. cent., while four-fifths of it has a rise of 30 deg. cent., then the increase in resistance of the coil as a whole will correspond to a rise of 40 deg. cent. Thus, by increase of resistance, the temperature may be more than safe, while actually one-fifth of the coil is far above the safe temperature for ordinary fibrous insulations. In other words, the resistance method gives only average results and may be very misleading. However, in those cases where it is known, by past experience

and otherwise, that there is very little liability of hot-spots, the resistance method of determining temperature is often quite satisfactory However, the method is limited to comparatively few types of windings.

Considering next the thermometer method of measurement, the theory of this is quite simple, but apparently it has been very much misunderstood. In windings, except in rare cases, the thermometer is not applied directly to the heat generating material itself, but is applied outside of an insulating covering Usually the temperature drop through this insulating covering does not receive any consideration, and yet everything depends upon this. Assume, for example, an insulated coil, thermometer and covering pad, as shown in Fig. 4. Assuming the copper inside the coil as being of uniform temperature, and the cooling air at *a* and *b* as also at a uniform, but much lower, temperature than inside the coil; then the temperature drop from the copper to *b* will be the same as through the insulation, thermometer

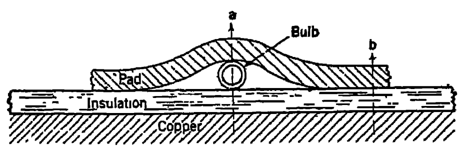


FIG. 4

bulb and covering pad to the air at *a*. Obviously if the temperature drops through the insulation and through the pad are equal, then the thermometer bulb will show a midway temperature. This is, of course, assuming that the surface drop to the air, previously referred to, is very small, or that it is included as part of the drop through the pad. Obviously, if the drop through the covering pad is made very much higher than that through the insulation proper, then the thermometer bulb more closely approaches the copper temperature. Thus it is seen that all kinds of results may be obtained, depending upon the relative drops through the pad and through the insulation. In a low voltage machine, with relatively thin insulation, the pad may take most of the drop. With very heavy insulation, the pad may take proportionately less and the thermometer reading departs accordingly from the copper temperature. It might be suggested that a big thick pad of very poor heat conducting material might be used. This apparently would tend toward more ac-

curate temperature readings, but, on the other hand, harmful effects may be introduced by the use of a large pad. The resistance to heat dissipation being increased in the area covered by the pad, obviously less heat will be carried away at this point and, therefore, the heat generated under the pad must be conducted to adjacent parts of the coil. This means an increased temperature at this point, due to the use of the pad. Again, the use of the pad, in some cases, may affect the normal ventilation of certain parts of the coil not directly covered by the pad. For instance, if there is a ventilating space between two adjacent armature coils, through which air is normally driven, a pad which covers this space even partially may create more or less of an air pocket, and thus materially affect the heat dissipation, and the temperature directly under the pad. Experience has shown that both of the above conditions are obtained when good judgment is not used in the application of the covering pad. This, of course, applies particularly to those cases where temperature readings are obtained while the machine is in operation. Of course, after shut-down, most questions of ventilation and of generation of higher temperature under the pad need not be taken into account.

There are so many conditions entering into the interpretation of the thermometer and resistance methods of determining temperature, that in certain classes of apparatus it has been very desirable to find more accurate methods. One of these is in the use of so called resistance coils. In this method a coil of fine wire of a known temperature co-efficient, and of known resistance at a given temperature, is placed at the place where the temperature is to be measured, and the temperature rise is determined from the increased resistance of the coil One serious objection to this arrangement, is that the resistance coil must have considerable length and breadth so that it really indicates the average temperature of a considerable area instead of a point. When placed between two coils, as indicated in Fig. 5, it usually occupies so great a proportion of the slot that it indicates an average temperature considerably lower than at *a* Furthermore, on account of the length of such coils, there may be a considerable difference between the temperatures at the two ends Thus the resistance coil, like the resistance measurement of the windings themselves, gives an average result, but this average may be limited to a comparatively small area, whereas, in the resistance method in general the indicated rise is an average of the whole winding. However, in the resistance method, the tem-

perature of the conductors themselves is measured, whereas, with the resistance coil the temperature measurement is outside the insulation The resistance coil method is, therefore, a relatively crude approximation, although when brought out it was really an important step in advance In its early application, many misleading results were obtained, due largely to lack of understanding of the principles governing temperature distribution and temperature drop. In some cases, the resistance coil was placed under the wedge as at *b* in Fig 5 In other cases, the coil was placed at the side of the slot next to the iron, or at the bottom. Very rarely was it placed midway between the two coils, probably because this was a more difficult application and

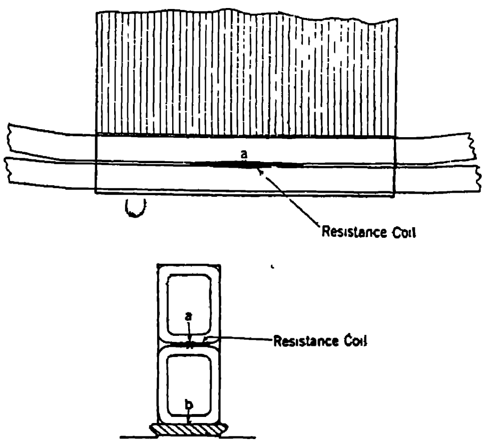


FIG 5

also because the greater accuracy of such location was not recognized From the use of resistance coils many good engineers drew the conclusions that the upper limit of permissible temperature for fibrous insulations was only 80 deg to 90 deg cent, because with the coils located in certain ways and places, deterioration of insulation at some other point was liable to begin, if the above temperatures were exceeded The error was in not recognizing the temperature drop between some hotter spot and the average location of the resistance coil When this condition was recognized the results obtained by resistance coils became more consistent with the facts

A later development than the resistance coil is the thermocouple as a practical device for measuring temperature One

great advantage of the thermo-couple is its very small size, so that it can indicate the temperature at practically a point instead of a very considerable area Moreover, as it is a zero current method of measurement, when used with a potentiometer no question of size or length of the connecting leads need come up The thermo-couple is so small and has so little mass, that it can follow very quickly any temperature changes where it is located If properly placed it furnishes the most accurate temperature indicator which we now have, as it can be located in all sorts of normally inaccessible places However, its use is practically limited to stationary apparatus. In rotating apparatus, or rotating parts it can be used only after shut-down, which introduces errors, as already shown.

Many-Conductor Coils

In all the preceding considerations it has been assumed that the copper inside the coils itself is at a uniform temperature, in any given unit of length. This is practically true, provided the coil is made up of a single conductor, or of a relatively few conductors with only a moderate amount of insulation between them When several coils or conductors are placed side by side, as in Fig. 6, it would appear at first glance that the middle coils should heat much more than the outer ones But, in reality, unless there are many layers of coils, the temperatures of the different coils will not vary greatly from each other For instance, in Fig. 6, the heat generated in the middle conductor is only one-third that of the total generated in the coil, and yet the two side surfaces through which this heat passes to the adjacent coils aggregate almost as much as the total outside dissipating surface of the whole coil, through which all the lateral heat flow is dissipated. Considering further that the insulation between the middle coil and its neighbors is relatively thin compared with the outside covering, it is obvious that the temperature drop from this coil to the adjacent ones will be comparatively small,—possibly not over ten per cent of the drop through the outside insulation

However, with a large number of coils side by side, the conditions become cumulatively worse. Here, the drop from the center conductor to the next one, may be small But the drop from the second conductor to the third is considerably greater due to the heat of two conductors being transmitted. From the third to the fourth there is a drop corresponding to the losses

of three conductors, etc Thus, there is a gradually increasing temperature drop from the center of the coil toward the outside surface, and if the coil be very deep, that is, if it consists of many insulated layers, the sum total of the drops may be quite large Or, putting it in another way, with a comparatively deep coil, the temperature rise from the outside surface of the coil itself toward the center will be very rapid at first, and gradually taper off, as indicated in Fig. 7. This is indicated very clearly in the case of an over-heated field of coil of fine wire. Here the first outside layers will usually be found in a fairly good condition, but at a comparatively little distance inside the coil there may be severe roasting or evidence of overheating, which may be

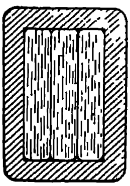


FIG. 6

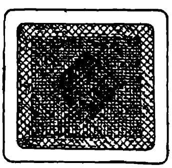


FIG. 8

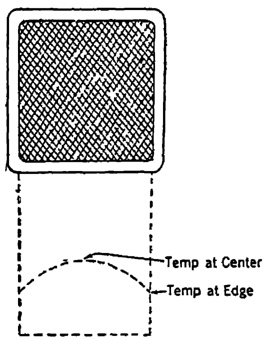


FIG. 7

almost as bad as at the center. (See Fig. 8.) In such case, the temperature measurement on the outside of the coil is no satisfactory indication of the hot-spot temperature A temperature measurement by resistance, while a closer indication than that by thermometer, also may be very misleading It may be stated that modern design tendencies are toward comparatively shallow field coils, largely on account of this condition

CONCLUSION

The whole object of this paper is to show the problem of temperature distribution and temperature measurement, as it actually is. It is the writer's desire to show that no hard and fast rules can be made for determining the facts in the case, and that

the best rules and methods now practicable are only approximate. The present limitations set for insulating materials are much higher than were considered practicable only a few years ago. This is not because the limits have been raised, but because, through a better understanding of the facts, the real upper limits of temperature as fixed by durability of insulation, are now known to be considerably higher than was believed to be the case only a short time ago If the real limits were in accordance with former beliefs, then all the evidence of the more accurate modern tests and data would indicate that the vast majority of the existing electrical machines should have "roasted out" comparatively early in their operation The higher temperature limits were there, but were not recognized Now we recognize them and attempt to make reasonable allowances for differences between the measurable temperatures and the actual hottest parts. The present method may be crude, but we are not going at it blindly, as was formerly the case. Formerly the manufacturer took the real responsibility for making a machine that was safe for the service, whatever the guarantees called for. Today the responsibility is still his, but he is attempting to educate the public to a knowledge of his real problems, and to a recognition that temperature determination is far from being an exact art. There is no sharply defined line between *good* and *bad* in the insulating materials as affected by temperature, consequently there is no sharp line between *safe* and *unsafe* temperatures.

Abstract From Discussion

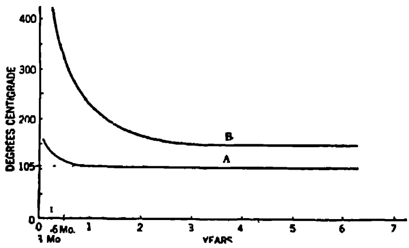
I have made up a sketch which brings out much better than any description, some of the fundamental differences between Class "A" and Class "B" insulations. These might be called the time-temperature curves for these insulations. These must be considered as approximations only, as, from the very nature of the materials themselves, no exact curves are possible. The important feature to be considered in the curves, is the general shape rather than any absolute values.

We have made a great many temperature tests of insulations to determine their durability; also we have made examinations of a very large number of windings which have been in service for many years, but for which we had only approximate data as to temperatures. Obviously it is impracticable to carry on an accurate life test covering a long period of years, so what we did in

most of our tests, was to carry the temperatures up to such points that destruction was either reached or indicated in a comparatively limited period of time.

Curve *A* indicates approximately the durability of class A insulations for various temperatures This should be recognized as being approximate, but it is optimistic rather than pessimistic.

Curve *B* applies to well built class B insulations, as now furnished by some of the electrical manufacturing companies. Such insulations contain a large percentage of heat resisting materials with a comparatively small percent of binding material and the insulation is applied so tightly that deterioration or destruction of the binder does not appreciably loosen up the true insulating material



Considering curve *A*, taking 105 deg. cent., as the ultimate temperature limit for long life without undue deterioration, then with a very slight increase in temperature, say to 115 deg. cent., the life is shortened very much, and at 125 deg. cent. such insulation is good for only a very few months at the most. At 150 deg. cent. it has an exceedingly short life.

Next considering curve *B*, our available data indicate that for over twelve months operation at 200 deg. cent., the insulation is in first class shape; in fact, much better than class A insulation at 110 deg. cent., for the same length of time. At 300 deg. cent. for six months, the insulation really shows better than class A insulation at 115 deg. cent. for the same length of time, and, at 400 deg. cent., the class B insulation for three months is better than class A insulation at 125 deg. cent. for the same length of time. If we now assume the continuous life for the class B insulation as 150 deg. cent., then it is seen that a 33 percent increase in temperature for one year is no more harmful than a 5 percent increase in temperature over the 105 deg. cent. for class A insulations for one year. Also a 100 percent increase in temperature above its continuous limit for six months is com-

parable with a 10 per cent increase in temperature for class A insulation for the same period. For still higher temperatures the percentage is far more in favor of class B.

What I want to bring out in particular by means of this diagram, is that the factor of safety for overloads is vastly greater for class B than for class A insulations, on the basis of continuous life being taken as 150 deg. cent. and 105 deg. cent., respectively. Part of this difference is inherently in the characteristics of the materials themselves, but no doubt part of it is due to the fact that the arbitrary 150 deg. cent. limit set for properly built class B materials is considerably too low in comparison with 105 deg. cent. for class A. But, whatever the explanation, the difference is there.

In regard to the very high temperatures for class B insulations, such as 300 deg. and 400 deg. cent. shown in curve B, attention should be called to the fact that unless there is an exceedingly high temperature drop through the insulation itself, any outside supporting layer or wrapper of fibrous materials is liable to become unduly heated and may disintegrate. Therefore, while the insulation proper might stand 400 deg. cent., for instance, yet if this was continued for any considerable length of time, so that the outside supporting material became excessively heated, such material would have to be of something else than the usual treated tape or fibrous wrappers. However, it so happens that very high temperatures are rarely attained in practice, except in the case of armature conductors buried in slots. In such case the surrounding iron assists very materially in cooling the finishing wrapper on the coils, unless the high temperature is maintained for a very considerable period.

Some are inclined to look askance at mica at 150 deg. to 200 deg. cent., but it must be remembered that in certain heating apparatus mica is used up to 500 deg. cent. and, in some cases, even up to 750 deg. cent. Practically all micas will stand up to about 600 deg. cent., without undue deterioration, and some grades will stand up to 1000 deg cent. From this viewpoint, the temperature of 150 deg. to 200 deg. cent. in armature coils appears to be very low and the whole matter turns upon the way such mica is used. If the percentage of mica in the insulation is relatively high and the mica is put on so tightly that the binding material can disintegrate and loosen up and yet the natural elasticity or springiness of the mica can hold the insulation tightly in

place, then such insulation can stand very high temperature without injury. But, if the mica is wound or placed so loosely that this disintegration of the binding or supporting material allows the mica part to loosen up materially, then the insulation qualities may still be very good from the dielectric standpoint, but may be in such poor shape mechanically that vibration or shocks may shift it or displace it sufficiently to injure it as an insulator. This defect is a mechanical one and not in the quality of the material itself.

Mr. Junkersfeld has spoken of some of his early experiences with high temperature, and he mentioned that the data which he and his associates obtained have had a marked nfluence in leading the manufacturers toward better grades of insulation. This is no doubt correct, but I wish to call attention to the fact that the manufacturers were also following this matter independently of the operating companies, with the same end in view. For instance, the company with which I am associated, insulated the 1894 Niagara generators with mica. We did not know whether such insulation was required, but we thought t was good material and so put it on. Later tests showed that this was a very fortunate decision, and now, after twenty years of operation, this insulation is still in very good shape, although subjected to very much higher temperatures than originally contemplated, 150 deg. to 200 deg. cent, being not uncommon according to later tests. Also in 1898 and 1899 the large engine-type Manhattan Railway generators had mica insulation, in the form of wrappers, on the armature coils. Following this, mica insulation was used for quite a number of years, mostly on large high-voltage alternators. About 1904 we built some large capacity 60-cycle turbo-generators on which we used mica wrappers on the armature coils. In service, one of these machines was injured from some mechanical cause and we had to rewind it. One of the fads about this time was special oiled-linen tape insulation, and quite a pressure was brought to bear upon us to rewind this machine with such oiled tape. With this insulation the armature broke down in a comparatively short time (within a few months, if I remember rightly). When the coils were removed, the outside layer of insulation next to the iron was found to be apparently in fair shape, but next to the copper the insulation showed indications of being excessively heated; in fact, it was badly carbonized in some places. We then reinsulated with mica and the machine was operated for many years without trouble. Here was a direct comparison between class A

and class B insulations. I do not know how hot those coils ran, but, judging from the appearance of the oiled-tape insulation, it must have been materially above 125 deg. cent. Here was a fortunate instance where the machine was first insulated with mica tape and then afterwards insulated with fibrous materials, so that actual comparison was obtained with the two materials This was ten to twelve years ago, so that it cannot be said that experience showing the relative merits of these two types of insulation is only of recent date.

In the same way similar experience was obtained with field insulation. Practically all our early turbo-generator fields were insulated with fibrous sheet materials. Numerous instances occurred where such insulations deteriorated so much that rewinding was required. This led to numerous tests for temperature. In some of these earlier machines there was evidence of practically uniform overheating throughout the whole winding, thus indicating practically uniform temperature. In such cases it was comparatively easy to approximate the ultimate temperature from readings of the field currents and the field volts, thus obtaining the increase in resistance and from this the temperature rise. Such tests soon developed the fact that temperatures of 110 deg. to 125 deg. cent were not uncommon on the earlier turbo-fields, while with the increased capacities and higher speeds, toward which we were continually tending, the indications were that still higher temperatures would be attained. This led to the development of mica insulation for the field windings of turbo-generators In 1906 and 1907 a number of the earlier hot fields were rewound with mica and such fields have been operating up to the present time, or until discarded in favor of larger units. The record with these mica insulated fields has been extremely good. In some of the tests which we made on these earlier machines to determine the suitability of mica for field insulation, we carried one field up to 250 deg. cent. for forty-eight hours, and would have continued the test very much longer, but the conduction of heat from the core through the shaft to the bearings was sufficient to overheat them However, at the end of this test the insulation was found to be in absolutely good condition. This was a very mild test, in view of our later investigations on mica, but at that time it was considered wonderful. I am simply bringing up such points to indicate that mica has been used quite extensively on turbo-generators for many years.

SOME PRACTICAL CONSIDERATIONS IN ARTIFICIAL VENTILATION FOR ELECTRICAL MACHINERY

FOREWORD—The material given was first presented in a discussion at one of the meetings of the Association of the Edison Illuminating Companies, September, 1915. It was afterwards revised for publication in the Electric Journal.—(ED.)

IN the artificial cooling of power-house and sub-station apparatus especially that of large capacity, a number of conditions have developed from time to time which have given trouble or which have provoked more or less discussion. A number of these points are here presented briefly.

QUANTITY OF AIR REQUIRED

There is a very definite physical relation between the heat which must be dissipated from a machine, the resultant temperature rise, and the quantity of air which is passed through the machine to carry away the heat. The law is that one kilowatt of loss dissipated into the air will raise 100 cu. ft. of air 18 degrees C. in one minute. Therefore, if there is a definite loss to be dissipated by the ventilating air and a desired limit to the permissible rise in the temperature of the air leaving the machine, then there must be a definite volume of air per minute through the machine. The problem then resolves itself into getting this air through the machine or apparatus. An allied problem lies in the means for getting the heat from the copper or iron to the air.

PRESSURE REQUIRED TO OBTAIN DESIRED QUANTITY OF AIR

The pressure required for a given quantity of air is dependent upon the size of air passages or apertures, upon the shapes of the ducts, i. e , number of bends, abruptness of bends, length of ducts, etc., and upon the velocity of the air. Too small passages means high velocity of the air, with consequent high pressure required. However, with many classes of artificially-cooled apparatus, the space available for air passages is comparatively small at some places, so that the air velocities are very high. This means ventilation losses, but in many cases these are unavoidable without radical changes in design which, in themselves, would mean increased losses of other sorts equal to, or greater than, the possible reduction in ventilation loss.

Usually, the greater part of the pressure developed by the ventilating fans is used up in the ducts or passages through the machine itself. However, not infrequently, part of the pressure is taken up by restrictions of some sort in the inlet or outlet conduits If the machine is self-cooling in the sense that the rotor carries its own fan, then such restrictions in the conduits may very seriously affect the quanity of air which passes through the machine. It is, of course, possible to make the ventilating fans of greater capacity, just to take care of such contingencies, but this would be penalizing good engineering to take care of bad, for the losses due windage would then be unduly large where proper conduits are furnished. Cases have been noted where as much as 30 to 40 percent of the available pressure has been taken up by improperly designed inlet pipes.

Where the ventilating fans are driven independently of the main rotor, that is, by motors, it is practicable to vary the air pressure to suit the requirements, provided the driving motor can have its speed adjusted over a suitable range. This makes the ventilation more or less independent of restrictions. It has the further advantage of allowing the quantity of air to be varied to suit the load conditions. By this means an increased quantity of air, but with correspondingly increased windage loss, is available with heavy loads, while less air with lower losses may be used at lighter load This arrangement is somewhat more efficient than the self-cooled arrangement with the fans on the main motor shaft, principally because of the excessively high fan speeds common in the latter case, especially on turbo-generators in which fan speeds far above efficient operation are used. In fact, in high-speed turbo-generators fan efficiencies of 20 to 30 percent are not unusual. Much better efficiencies can be obtained from separate slower speed fans (50 to 60 percent). However, the reduction in windage losses is not proportional to the increased efficiency of the fans, for part of the windage loss is due to "churning" of the air passing over the rotor, and this will be present regardless of the method of supplying air to the machine and is, to a certain extent, a function of the quantity of air which passes through the air-gap. This part of the windage loss is, therefore, greater in those machines where all the cooling air passes through the air-gap than is the case with those types where a considerable part of the air passes directly through the armature core, as in axially ventilated stators. In either type of ventilation, variation in the quantity of air with load is advantageous.

DISPOSAL OF HOT AIR

This was a matter of little importance in the days of small capacity per unit-area of generating room. However, in these latter days, where capacities of from three to ten times those of former days are developed in the same space, the question of disposal of hot air from the machines is becoming important. Large turbo-generators may require from 50,000 to 100,000 cu. ft. of air per minute. Five or six such machines in one generator room, operating at full load, means 250,000 to 500,000 cu. ft. of air per minute pouring into the room, this air being from 20 to 25 degrees C. above the normal air temperature. Obviously some provision should be made for getting this hot air out of the room. In the average generator room, the total cubical capacity of the room will be only five to ten times the total volume of air passing through the machines per minute. This gives a good quantitative idea of the extent of ventilation required in order to prevent undue temperature rises of the room air. In some of the more modern stations provision has been made for exhausting the hot air from the machines into the boiler room.

DIRT IN THE AIR

The enormous quantity of air required for ventilating large turbo-generators brings up the question of amount of dirt carried into the machines by such air. Assume, for instance, 60,000 cu. ft. of air per minute through a given machine. This weighs approximately 4800 pounds. The usual turbo-generator will, therefore, pass through itself, each thirty to forty minutes, a weight of air equal to its own total weight. Or, presenting the matter in another way, 45,000,000 cu. ft. of air passes through in twelve hours. Assuming as a rough approximation, that only one hundredth-millionth of the volume of air consists of dust or foreign particles, then the above means that 0.45 cu. ft. of dust passes through the machine in twelve hours, or 45 cu. ft. in 100 days of twelve hours each. If the air inlet is in a dusty place, the above is not at all an impossibility. Of course, a considerable part of this dust will go directly through the machine, but in the air swirls and eddies inside the machine some of it will be deposited, and eventually this becomes a considerable handicap to the ventilation. This dust acts harmfully in two ways. In the first place, it may partially close the ventilating passages and thus decrease the quantity of ventilating air. In the second place, it may form a

coating upon the heat-radiating surfaces so that the cooling air cannot come directly in contact with such surfaces. Ordinarily, in dissipating heat from a surface to the air, a thin film of hot air adheres to the surface, and the heat is conveyed from the surface through this film to the moving air. With high-velocity air striking the surface, this film of hot air is scoured away from the surface, so that new air continually comes in contact with the surface. If however, a coating of dust, or of other heat-insulating particles, gathers on the surface, then the ventilating air cannot come in direct contact with the surface and the heat-dissipation is at a lower rate. Dirt is particularly liable to adhere to the surfaces in case minute particles of oil are carried into the machine.

AIR WASHERS

Air washers are now being installed very generally in large generating plants to clean the air which passes through the machines. These washers have beneficial results in two ways. In the first place, they clean the air, thus preventing, to a great extent, the deposit of dirt in the machine. In the second place, they cool the air in hot weather, thus directly improving the capacity of the machine by allowing a greater temperature increase without exceeding a specified limit of temperature. A number of attempts have been made to cool turbo-generators by means of water in suspension in the ingoing air, that is, by "fog." Such methods as yet have shown no particular promise.

Instances have occurred where fine, dry snow has been drawn into artificially-cooled apparatus and there melted, with the formation of water on the windings. This can only happen in cold weather and could be avoided in several ways. An opening from the inside of the building could be provided in the air intake so that the ventilating air is not taken from the outside. Another method would be to use the air washer at such times, by which means the snow would be abstracted. It is usually not considered advantageous to operate the washers during extremely cold weather, but in case of incoming snow there may be considerable advantage in operating the washers.

ZERO AIR, AND WATER DEPOSIT

A number of instances have been noted where, with the incoming air at an extremely low temperature (near zero F.), the end windings of turbo-generators were found covered with a film of water. In one case this proved disastrous. Apparently this

was not condensation of water from the air, in the ordinary sense for the armature windings were much hotter than the incoming air. One explanation is that this is due to "frozen fog," or ice particles in suspension, which melt when they come in contact with the heated parts of the machine. One remedy for this trouble is in the use of doors from the interior of the building to the inlet pipe, which can be opened in extremely cold weather to admit warmer air.

FIRE HAZARDS IN ARTIFICIALLY-COOLED MACHINERY

When a fire is started in such apparatus the artificial ventilation tends to spread the fire very quickly, especially in turbo-generators. Various remedies have been proposed, such as firedoors or dampers in the inlet conduits, the use of "fireproof" end windings, chemical extinguishers, etc. Firedoors have proven only partially effective, possibly due to the fact that it is difficult to shut off the air completely. For instance, in a machine taking 50,000 cu. ft. of air per minute, if 99 percent of the air is shut off, the remaining 500 cu. ft which can pass through the machine may be sufficient to maintain quite a destructive blaze. Furthermore, there are liable to be small leaks around the end housings of the machine which will admit a little air.

It has also been suggested that equally good results would be obtained by enclosing the outlets from the machine in case of fire, thus retaining the products of combustion inside the machine, these forming a fairly good fire extinguisher in themselves.

As regards chemical extinguishers, these are practically useless unless the incoming air can be almost completely shut off. With 50,000 cu. ft. of air, for instance, passing through a machine, the small amount of gas which the extinguisher could furnish would be so diluted as to be worthless. One point to keep in mind in applying extinguishing gases is that they must be applied at the incoming side of the fan.

In some cases of fire the operators have turned on water from high-pressure mains, on the theory that, while water may ruin the insulation, yet fire may result in still greater damage.

Various attempts have been made to produce "fireproof" insulations for the end windings of turbo-generators. The difficulty lies in the fact that available fireproof materials, such as mica and asbestos, cannot be used alone. Mica requires some supporting or binding material, while asbestos requires some filling

varnish in order to obtain suitable insulating quality. It is these binding or filling materials that are the real source of trouble, for these give off gases if the temperature is sufficiently high, and these tend to maintain or increase the blaze. Thus the outlook is not very promising.

When the initial blaze is produced by a short-circuit or arc inside the machine, a sudden interruption of the excitation, by killing the voltage, may extinguish the arc before a general conflagration is established. If the excitation is from a motor generator across the terminals of the machine, then a short-circuit in the machine may automatically shut down the exciter set. In the same way, if the ventilating fan is driven by a motor across the terminals of the machine, the ventilation may decrease automatically.

The above covers various suggested methods for preventing damage by fire inside such apparatus. All of them are admittedly defective, but each of them possesses some merit. A simple satisfactory method of fire protection for such apparatus is much to be desired.

NOISE

Recent high-speed turbo-generator rotors are all of the cylindrical type, with relatively smooth exterior surfaces. Nevertheless, due to their enormously high peripheral speeds and the great quantity of air through the air gaps, there is always very considerable noise developed inside the machines themselves. As such machines are always very completely enclosed, except through their outlet and inlet pipes or openings, these latter are usually responsible for any complaints regarding noise. Several cases have developed where the inlet conduits, opening directly to the outside of the building, have permitted undue noise. In other cases, sheet metal conduits have acted as sounding tubes and apparently have exaggerated the noise. Changing to plaster-filled expanded metal conduits has helped in some cases. In other cases, carrying the conduits up to the roof of the building has proved effective. A secondary result of this arrangement is that cleaner air is obtained, unless the inlet is exposed to an undue amount of dirt from the chimneys.

SOME ELECTRICAL PROBLEMS PRACTICALLY CONSIDERED

FOREWORD—This paper was prepared for the eighth annual convention of the Association of Iron & Steel Electrical Engineers held at Cleveland, September, 1914. The object of the paper was to present, in as simple form as possible, certain problems, such as insulation, commutation, speed control of induction motors, etc., which particularly concerned iron and steel electrical engineers. —(ED.)

IN steel mill electrical work there are a number of subjects which are of very particular interest at present. In both alternating and direct-current apparatus, there is the general subject of insulation troubles, which is always open to discussion. In direct-current work, commutation and commutator troubles are subjects which are always with us. Also, as the induction motor is probably used more than any other in mill work, the problem of obtaining variations and adjustments in speed with this type of motor has become a very important one. In alternating-current work, there is the question of the most suitable frequency, which has come up prominently in the past two or three years. While these various subjects may appear to be more or less disconnected, yet, in fact, they are already allied in mill work, and all steel mill electrical engineers are liable to be called upon to deal with them.

In the presentation of these subjects, a semi-technical method is followed, and all mathematics, except where masked under some other form, are omitted. The various subjects are treated in the order of their convenience, and without regard to their relative importance.

THE INSULATION PROBLEM

Practically all electrical apparatus uses insulation in one form or another. Such insulation in general constitutes the weakest part of the machine, both mechanically and electrically. Insofar as the generation or utilization of energy is concerned, its functions are passive, it serving merely as a protection. But in another way, its functions unfortunately are not passive, namely, in its effect on heat flow and dissipation. In most cases, the parts which have to be insulated are heat-generating. This is especially true of the

windings of electrical apparatus. Experience shows that all electric insulators are heat insulators to a great extent, and extremely good heat insulators in the case of the most practicable materials. It is well known that the best way to apply heat insulations is in the form of superimposed layers, and this happens to be the most practicable way of applying most electrical insulations. It is also well known that air pockets in heat insulations improve their heat-insulating qualities. It is partly on this account that, in the application of electric insulations, air pockets are avoided as much as possible, and endeavor is made to fill such pockets with varnishes or impregnating gums which act as better heat conductors than air or gases. In general, it may be said that heat is transmitted more effectively by conduction through solid bodies, or between solid bodies in contact, than by convection through gaseous bodies. Therefore, the more solid, or the better filled is the insulation, the better it will conduct heat as a rule, and, in fact, there is not such a great difference between the heat-conducting qualities of the various commercial insulations, on the basis of equal solidity. The principal differences are found in the ways the materials are applied. While some materials may conduct heat two or three times as well as others, yet this difference is very small compared with the difference in heat-conducting qualities between ordinary insulations and any of the so-called electrical conductors, such as metals. For instance, a difference of temperature of 1 °C. between the opposite sides of an inch cube of copper will allow a heat flow 2500 times as great as with a corresponding cube built up of oil tape. And an inch cube of wrought iron, which is considered a poor electrical conductor, will conduct about 400 times as much heat as the block of insulation. Therefore, when compared with electrical conductors, we may say that the heat-conducting qualities of the usual built-up insulations are fairly uniform.

The heat-conducting ability of insulation is a function of the thickness or distance the heat has to traverse, just as in all other bodies. Therefore, when a heat-generating body is covered with insulation, it is desirable to make such insulation as thin and compact as possible, where it is desirable to keep the temperature as low as possible. This is an elementary fact which has been very much neglected and overlooked in the past.

In electrical apparatus, it may be said that it is not the temperature in the heat-generating body itself which is harmful, but

it is the effects of such temperature upon the enclosing or contiguous insulation which must be taken into account. Most of the flexible insulations in every-day use do not have high heat-resisting characteristics. The effect of the heat usually is more harmful to the mechanical characteristics of the material than to the electrical characteristics. Most fibrous insulations, when exposed to fairly high temperatures for long periods, or exceedingly high temperatures for much shorter periods, show a tendency to become very brittle, and, in time, they may even carbonize to a greater or less extent. However, for moderate voltage stresses, even this very dry or semi-carbonized condition of the insulation does not appear to seriously affect its insulating qualities. The real harm lies in deterioration or possible injury of its mechanical properties —that is, it may become so brittle that it will not stand mechanical shocks or vibrations, and may crack or scale off so that its insulating qualities are impaired simply through mechanical defects. Here is where certain filling or impregnating varnishes or gums are particularly useful. As the fibrous insulation tends to become brittle at high temperatures, the varnish or gum may tend to soften at the same temperature, and thus conteract, to a certain extent, the brittleness of the fibrous material itself. A second function of such gums or varnishes is to act as fillers for all spaces and interstices, and thus to assist in conduction of heat, but, still more, to act as a cushioning material to keep the conductors from vibrating under shocks, etc. Of course, the impregnating gums or varnishes have a certain value as insulating material, but probably the above functions are of far greater value. For instance, the ordinary cotton covering on a wire will stand far more abuse when treated with some kind of gum or varnish than when used in the dry condition, for, in the former case, the individual fibers of the covering are actually pasted in place, and are therefore much less liable to be separated and thus allow metal parts to come in contact. Usually what is required between adjacent conductors in a coil is a positive mechanical separation of a very limited amount. In many cases, if the bare conductors could be maintained at a distance apart corresponding to the thickness of the usual cotton covering, this would be sufficient for protection against the voltages between the wires. The layer of insulation on the wires themselves furnishes the simplest and easiest method of obtaining this mechanical separation, and the varnish or gum treatment makes this separating medium of more mechanical and durable construction, and, at the same time, improves the heat-conducting qualities.

There are limits to the heat-resisting qualities of all practicable insulations. Ordinary fibrous materials of a cellulose nature or base, will stand about 95°C, to 100°C. without becoming too brittle to be durable. However, the same materials, when treated with suitable varnishes or gums, apparently stand temperatures of about 105°C. without undue deterioration mechanically. At this temperature the material does not appear to carbonize, and the varnish or gum assists in maintaining mechanical continuity of the material. At materially higher temperatures, deterioration gradually takes place at a rate depending upon the actual temperature attained. Even at 150°C., treated fibrous materials may have a total life of several months before the material becomes unsuited for its purpose. If such high temperature exists only for short periods, and during the remaining time the insulation is subjected to relatively low temperatures, then the life of the apparatus measured in years, may be fairly great. In other words, high peak temperatures may not be very harmful, provided the sum total of such peak periods does not add up to as long a period as required to injure the materials if maintained at the same peak temperature steadily. However, the life of insulation does not decrease in direct proportion to the increase in temperature, but at a much faster rate.

Other insulations in common use are mica, asbestos and certain varnishes and gums. Pure mica will stand enormously high temperatures, such as 700°C. or even higher. Good grades of asbestos stand at least 400°C. as shown by actual test, and possibly very much higher. However, neither mica nor asbestos, in itself, is a good material for application to windings, due to mechanical conditions. In order to obtain flexibility, mica must be built in thin sheets and then assembled in the form of a paper or tape. This requires some continuous supporting base, usually a thin tough paper, to which the mica is attached by some form of binding gum. The result therefore consists of both high and low heat-resisting materials. If the continuity and durability of the resultant mica insulation, after application to a coil, is dependent upon the durability of the binding and supporting material, then such insulation is limited to temperatures corresponding to fibrous materials. If, however, the binding and supporting material can deteriorate without materially injuring the insulation as a whole, then such composite insulation can stand comparatively high temperatures. In present practice, such temperatures are limited

to approximately 150°C. for steady operation, not because this is an actual limit, but largely because of lack of extended experience at materially higher temperatures. Apparently, such materials, when properly applied, will stand 300°C. on peak service about as well as the treated fibrous materials will stand 150°C.

Asbestos, as an insulation, is pretty poor material, but as a mechanical separator, where high temperatures are obtained, it may be very effective. Due to its open fibrous character, there is no true over-lapping of insulating surfaces, and, to make asbestos effective as an insulator, it must be filled in with some insulating filler or gum, in which case, the gum is the real insulator. However, asbestos may answer for a very good supporting material for other insulations, such as mica, when subjected to very high temperatures. Also, asbestos may be a suitable insulation on conductors with very low potential between them, as in field windings and in armature windings with low internal potentials. It should be considered as essentially a separating and supporting material, rather than as an insulation.

In recent years, a number of synthetic resins, such as Bakalite, have been developed, which have a field in insulation work. Such materials usually have high heat-resisting qualities, but, in their final condition, are liable to be hard and brittle. Some of them are used extensively as impregnating or filling varnishes, and when so applied, are in fluid form, and require further baking to change them to the final form. Some very extravagant claims have been made for them by those who were not sufficiently acquainted with the materials and their properties. They are very valuable in many ways, but, like all other materials, they have their limitations. In their application to armature windings, it is advisable, in many cases, to apply the coils before being given the final baking on account of the greater flexibility of the unbaked coils. But the final treatment usually leaves the armature winding in such rigid condition that, in case of repairs, it may be necessary to completely destroy the whole winding. This looks like a bad feature, but to counter-balance it, it may be said that, for certain kinds of work, such prepared windings are less liable to damage, and therefore the necessity for repairs is much reduced. As impregnating compounds, where stiffness or rigidity is advantageous, such materials have proved very satisfactory, but, where considerable flexibility is desirable, compounds of this nature may not prove so desirable. If the impregnating material

is brittle and is liable to crack, under stresses due to change in temperature, or movement, or shock, then it loses a certain part of its value. Where flexibility is important, gums or varnishes which soften with heat are desirable.

In armature or field windings, it is very unusual to find constant temperatures throughout the whole winding, due to the different heat-conducting and heat-dissipating conditions in different parts. Therefore, the higher temperature points or "hot spots" must be considered in fixing the insulation temperature limits. It is the highest temperature to which the insulation is subjected that must be considered in fixing the limits, and only in rare cases do the ordinary methods of temperature measurements indicate the highest temperatures actually attained. Ordinary thermometer measurements approximate the temperature at some accessible point, but this may not be, or, likely, is not the hottest part. A determination of the temperature by increase in resistance gives only an average value. Therefore, by actual measurement by the usual methods, the above mentioned temperature limit of 105°C. for treated fibrous materials is not allowable. For instance, the usual full load guarantee of 40°C. rise with a cooling air temperature of 40°C. will give 80°C. as the temperature measured, thus allowing a margin of 25°C. for some higher internal temperature—that is, for the hot spot. The usual overload guarantee of 55°C. by thermometer, with air at 40°C., will give 95°C. measured, or a margin of 10°C for the hot spot, which apparently is right on the ragged edge. But then, this 55°C. guarantee is usually given only for overloads or intermittent service, and it is this condition which allows the proper margin. If, however, an accurate means should become practicable for determining the actual hot spot temperatures, then it would be practicable to rate machines at the 105°C. measured temperature. As this cannot be done at present, we must fall back on a lower measurable temperature, and allow a suitable margin.

In certain classes of apparatus where the higher temperature regions are pretty definitely known, it is possible and practicable in many cases, to insulate, in the hotter regions, with materials which have higher heat-resisting characteristics, as already described. This is the case in many high voltage machines, and in machines with very wide armature cores, such as some turbo-generators, high speed large capacity alternators, etc. In such machines, the middle part of the armature core is liable to be

much hotter than any other part. Therefore, it is rather common practice in such machines to insulate the buried part of the armature coils with composite mica insulation, which can be easily applied on the straight portions of the coil. On the curved end parts of the coils, where taped insulations are required on account of the curvature, much lower temperatures are usually obtained, and thus fibrous tape insulations are amply safe for this part.

In apparatus subject to very heavy overloads for relatively short periods, excessively high temperatures may be attained by the copper inside the insulation, but if followed by much lighter load, the high temperature may drop so rapidly that no apparent damage occurs. Experience has shown that, not infrequently, local temperatures of 200°C. to 300°C. are attained for a very short time. When such temperatures occur close to any soldered connections, there is danger of damage due to unsoldering, for ordinary commercial solders will soften at about 170°C. to 180°C., while pure tin solders will soften at about 220°C. to 230°C. Therefore, temperatures which, due to their short duration, apparently do not harm the insulation, may actually unsolder connections

The above covers briefly the temperature part of the insulation problem. But insulating materials also serve another purpose, namely, to shield the conducting or live parts of the machine from other foreign conducting materials, such as dirt, grease, oil, water, etc. Oils and greases are usually considered as non-conducting, but when they are liable to carry with them conducting materials, such as copper and carbon particles, they become conductors in effect. Also, ordinary dust, or dirt, or deposit from the air, is a relatively poor conductor, but conducts far better than the usual insulations, and is therefore, to a certain extent, dangerous. As a conductor, water is considered as comparatively poor, and yet no one would class it as an insulator. Both water and oil may be directly harmful and may be indirectly injurious by their actions upon the insulating materials themselves. In the case of cloth tape insulators, the cloth may be considered as simply forming a base or reinforcing structure for the insulation proper, which is usually some varnish or oil compound. The insulation value of the material depends principally upon the continuity of the layers of varnish or oil. The cloth structure itself has no true continuity. In applying such tapes or insulations, the layers overlap each other in such a way as to give the best sealed circuit.

During the process of taping, the surface may be varnished repeatedly to further seal the overlapping joints, and to obtain greater continuity of the insulating film. Also, in the composite mica insulations, the mica laminæ are very thin and arranged in a number of layers in such a way as to overlap as completely as possible to form insulating films. The binding material between layers or films is largely for the purpose of sticking or binding the mica laminæ to each other. Therefore, with either type of insulation, continuity of the insulating film is the first requisite, and any action or treatment which tends to break the films will naturally tend to weaken the insulation. In high voltage armature coils, in particular, it is of utmost importance that the completed coils should not be sprung or bent to such an extent that the insulation films are liable to be cracked or "buckled" at any point, for this immediately produces a local weakness. In all cases, extreme care should be taken in handling such coils, especially in placing them on the cores. Moreover, in machines which are liable to carry excessive currents, even momentarily, and which are thus liable to distorting magnetic stresses, the windings must be so braced that movements sufficient to crack or buckle the insulation are not permitted. There is but little real flexibility in such insulations when built of any considerable thickness. Insulation on cables might be cited as an exception, but here the insulating varnishes are soft and possibly semi-viscous, so that a certain amount of bending does not break the insulating films. To maintain this condition of soft flexible insulation, cables are guaranteed usually only for very low maximum temperatures, compared with the temperatures usually found in electrical apparatus.

The continuity of the insulating films may be injured in other ways than by bending. If, for instance, a newly insulated coil which has been insufficiently baked or "seasoned," is subjected to a comparatively high temperature for even a short time, certain volatile matter in the varnishes may be given off in the form vapor, and these vapors may force or break their way through the insulating films. The writer has in mind one case where a taped insulation was used on a rewinding, with the shortest possible time for the baking before applying the coils to the machine. The insulation tests were high, but a heavy load was thrown on the machine at once and carried for several hours. At the end of this run, the insulation test showed that the insulating material had

deteriorated very greatly, —so much so that the machine was considered to be in a dangerous condition. Upon removing some of the coils, an examination showed what looked like little volcanoes all over the surface of the insulation. Further investigation showed that these were real volcanoes, for the high internal temperature had vaporized some of the original solvents which had not been entirely removed from the varnish, and such vapors had actually erupted through the superimposed strata represented by the insulating films or varnishes. Therefore, at each one of these points of eruption, there was a breakdown of the insulating strength of greater or less depth, depending upon where the vapor was formed. This is cited simply as a very good illustration of what can happen in "green" insulation.

Another source of difficulty which is not unusual, is that due to water, or oil, or other foreign materials getting into the insulation. Submersion of electrical apparatus, due to floods, is not uncommon in industrial plants, due to their proximity to rivers, in many cases. In some cases, experience has shown that a flooded machine can be dried out with apparently no harmful after effects, while in other cases, it has been found almost hopeless to save the apparatus. This depends to some extent upon the kind and character of the insulation and the means for getting rid of the water without injuring the insulation itself. If water has percolated into the coil and becomes sealed or trapped inside, then high internal temperatures obtained by any means may simply vaporize the water without getting rid of it. If the insulation is porous, the water may be driven off readily. If the drying heat is applied from the outside, then, before the center is heated sufficiently to vaporize the water, the outside insulating films may seal together under the higher outside temperature, so that the internal vapors cannot escape except by disrupting the film If, on the other hand, heat is applied from the inside, by means of current for instance, and the heating is too rapid, vapor may be formed more rapidly than it can percolate through the insulation, and it may injure the insulation in escaping. Also, in the case of electrical heating, non-uniformity of temperature must be taken into account. For instance, the armature winding of a high voltage alternator might be operated on a short circuit for the purpose of drying out. The drying out current may be so high that the center of the armature core is considerably above 100°C. or the boiling point of water, while the end windings may be 30 percent

or 40 percent cooler. In such case, the water in the hot part of the coils is simply vaporized and driven to the end windings and there condensed. This is not an unusual condition in drying out high voltage windings which contain moisture. One instance may be cited, where, several years ago the power house of the Westinghouse Electric & Manufacturing Co. was flooded for several days, and several large 2200-volt turbo-generators were partly submerged. One of these machines was dried out on short circuit for about a week at a temperature of possibly 120°C. inside the coil. At the end of this time, no leak to ground showed and the machine was put in service. A few weeks afterwards, a short circuit occured inside one of the coils, in the end winding. When dismantled, this coil was found to be sopping wet in the end portion, although the buried part of the coil was fairly dry. The baking process had simply distilled the water from the center to the end parts. An examination of others of the submerged coils showed the same condition. It is possible that untaping of the end winding sufficiently to have allowed the escape of vapor would have allowed this machine to dry out properly, but apparently this would not be the case unless the end windings in themselves could have been brought up to a temperature considerably above 100°C. and this might have meant 150°C. in the buried portion, which would probably have been injurious, except to mica insulations, which did not happen to be on these machines. Furthermore, it is not always easy to get rid of moisture, even at 100°C. with fibrous insulations. One very effective manner of doing so is by means of a vacuum. Experience has shown that if apparatus to be dried out is heated to tne boiling point, in a vacuum, the moisture usually is removed very completely. For most effective results the water should be vaporized, for, under some conditions, and with some materials, the force of capillarity may approximate 15 lbs. so that a good vacuum alone may not be able to overcome the capillary action. From the scientific standpoint, the use of vacuums in drying goes much further than the above. For example, the boiling point of water is very much reduced in a vacuum, so that materially lower temperatures may be used for removing water than would otherwise be the case. For rapid drying under ordinary air pressures, considerably over 100°C. is needed, while in a fairly good vacuum, 100°C. or less, may allow a very rapid evaporation of moisture and a correspondingly rapid and thorough drying.

In the same flood which submerged the generator above referred to, vast quantities of other apparatus of various types and designs were also flooded, and, in drying out this apparatus, a great deal of valuable experience and data were obtained. A summation of this and other experience may be of value and interest, and is therefore given below.

Low voltage alternating-current windings, such as induction motors and alternating-current generators for 600 volts and less, dried out very readily by the application of current to the windings.

In general, low voltage, direct-current armature windings were dried out by the application of current or by baking in ovens. However, there was great difficulty in drying out commutators, and eventually the only real satisfactory way proved to be by heating them in a vacuum. Therefore, the finaldrying out of direct-current armatures was principally by vacuum.

The complete drying out of field coils was very difficult, either by current heating or by ovens. However, the outside of the coils could, in many cases, be dried sufficiently to show practically no ground, while the inside of the coil was still wet. In most cases, field coils could be operated in this condition and could eventually dry themselves out. This would probably be satisfactory for drying out individual machines, but was not considered satisfactory for stock apparatus. Vaccum drying under high temperature proved most satisfactory, and this was adopted.

High voltage windings for generators and transformers were dried out in vacuum, no other methods proving entirely satisfactory, except in individual instances.

It may be borne in mind that his was a situation where superficial correction was not permissible. During the various tests and methods which were carried out, searching investigations of the results were made in order to determine the sufficiency of the method used. Field coils and armature coils were opened up at various stages of the process for examination. For instance, one of a lot of street railway armatures which were dried in an oven until apparently all right, was dismantled for examination. The windings appeared to be fairly well dried out, but upon opening the commutator V-ring, very considerable moisture was found under the commutator bars and in the mica bushing. Apparently, oven baking would not remove this satisfactorily. The commutator was then sealed tightly and the armature was then put in a vacuum oven and dried for a few hours. After this all water had

disappeared from the commutator. Another commutator was then opened and purposely filled with water and then closed and sealed as tightly as possible before placing in the vacuum oven. After an over-night's treatment, the inside of the commutator was found to be entirely free from moisture. This test illustrated the ability of the vacuum oven to remove water. It was then adopted very generally for drying out such apparatus as was liable to have water sealed or trapped inside the insulation. It must be understood, however, that certain kinds of apparatus were dried out just about as well using temperature alone. In these cases, however, as intimated before, the vaporized water could readily escape to the air.

There is one condition, however, where even vacuum oven drying may not produce the desired result, for the operation of drawing off the water may injure the insulating varnish films. To illustrate, some years ago one of the large power plants at Niagara Falls was flooded to a considerable depth by an ice jam, which backed the water up into the power house. The machines were flooded to a depth of twenty or thirty feet for a period of several days, and the windings were pretty thoroughly impregnated throughout with water. Strenuous attempts were made to dry out these windings by heating to temperatures of 125°C. or higher. The end windings were untaped at points to allow the moisture to escape. Also, attempts were made to create a vacuum around the machines by means of air-tight covers or casings and vacuum pumps, but this latter was not very satisfactory. After a few weeks, apparently but little progress had been made. A chemist then advanced the suggestion that, if linseed oil varnishes had been used in the insulation, then, under the conditions of flooding which had occurred in this plant, the varnish itself would have absorbed water, and he was of the opinion that heating alone, unless carried up to the destructive point, would not drive off this water. Investigations were then made along this line, and it was actually found that the varnished films were thoroughly filled with water, and moreover, this water could not be removed without more or less injury to the film itself. For moderate or low voltage machines, apparently, the removal of the water would not injure the insulation sufficiently to prevent operation, but in high voltages, such as 6600 volts or higher, the insulation would be left in a relatively weakened and unsafe condition. In the machines

in question, it was found advisable to remove the insulation entirely and replace with new.

As a rule, field coils can be dried out in a fairly satisfactory manner by heating with current for a sufficiently long period. When a field coil is thoroughly wet inside, its resistance may fall considerably, due to low resistance between turns and layers, but when current is applied, there is but little danger of burnouts, as the leakage of current through the insulation is distributed over such large surfaces that there is no danger of burning at any one point, unless there is some defectively insulated point in the coil. Therefore, after the coil is sufficiently dried so that its leakage to ground, or any metal supports, is sufficiently low to be safe, then usually the coil can be put in operation and allowed to dry out in regular service. If, however, the field coil rotates and is subject to centrifugal or other forces, the wet condition of the internal insulation may allow internal distortions or movements which might cause partial short circuits.

Commutation and Related Problems

In the practical design and operation of electrical apparatus, there is no problem which is apparently more enshrouded in mystery than that of commutation. Theoretically this problem has been treated in various ways and analyzed to various degrees, but the practical results not infrequently disagree with the theoretical, principally because the latter are predicated upon conditions which are not, or can not, be obtained practically. Moreover, even when the problem can be correctly analyzed, and a proper solution indicated, it may not be practicable or feasible to apply such solution. In other words, the theory may show just where a trouble lies, but the application of a suitable remedy is another story.

The difficulty is that the theories of commutation are built upon many conditions which are inter-dependent. But many of these conditions differ, in different types, designs or sizes of machines, and, even in a given machine, a change in one condition may greatly modify other conditions. For instance, the local or short-circuit currents which are present in the coils short-circuited by the brushes during the operation of commutation, have a preponderating influence on the commutation, and yet, these local currents are greatly influenced by many conditions, such as the dimensions and grade of brush, condition of contact surface,

rigidity and type of brush holder, etc. Obviously, with such variable elements entering into the problem, any rigid analysis is most difficult. In such cases, the theory is valuable in locating any probable causes of difficulty.

A great variety of conditions or phenomena are encountered in commutating machinery, which require more or less knowledge of the theory of commutation in order to understand them. For instance, the causes for sparking, flashing, burning of brushes, undue wear of commutator copper, etc , are all directly related to the commutation problem. Even questions of composition, or grade of brushes, type of brush holder, etc., are related problems.

As it is the writer's purpose to treat the above points from the practical side, he considers it advisable first to give a brief explanation of the commutation problem from the standpoint which he has found to be simplest and most illuminating.

Theory of Commutation

A direct-current armature, when carrying current, becomes a true electro-magnet, with the poles located on the armature at positions corresponding to those coils which are in contact with

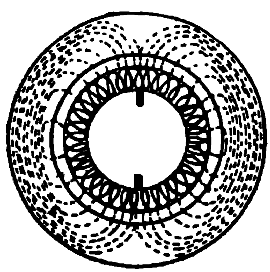


FIG. 1.

the brushes. If the armature were surrounded by a smooth ring of iron, (Fig. 1) then a magnetic field would be set up between the armature and the surrounding ring, this field having maximum values at points corresponding to the brush contacts and zero values midway between. The magnetic field would rise, from the zero points, uniformly to the highest values, because the armature winding, which is a magnetizing winding, is uniformly distributed over the armature core. If, now, deep notches were cut in the surrounding ring at points corresponding to the highest field, (Fig. 2) there would be comparatively weak field at these points, due to the high reluctance of the gap or notch. The ex-

ternal ring in this case represents the field structure of an ordinary D. C. machine, and, in such machines, the armature when carrying current actually tends to set up magnetic fields in this manner, and the coils in contact with the brushes are practically always located in the space between poles,—that is, in the notches in the surrounding ring in the above illustration. Also, the coils in contact with the brushes are those in which the current is reversed in direction when passing under the brushes, or, in other words, are the commutated coils. Therefore, it may be seen that the commutated coils always lie in what would be the strongest magnetic field set up by the armature winding, if there were no polar notches. But, even with such notches or interpolar spaces, the armature winding, when carrying load, tends to set up some magnetic field, part of which is in the space over the armature, and part of it across the armature slots. This latter flux from slot to slot, is not influenced by the notches in the surrounding iron,—that is, by the interpolar spaces. In addition, the armature winding sets up a magnetic field around the end windings.

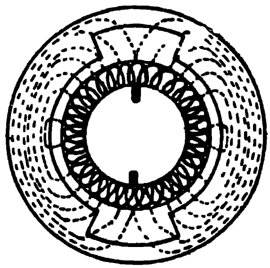


FIG. 2

The armature winding, when carrying current, therefore always tends to set up a magnetic field, through which the armature conductors rotate and generate e. m. f.'s, just as when they cut the main field set up by the field windings. These coils short-circuited by the brushes also generate e. m. f.'s and as their terminals, which are commutator bars, are connected together or short-circuited by the brushes on the commutator, the e. m. f.'s generated by cutting the armature flux tend to cause local or short-circuit currents to flow in such coils. Such currents will be known hereafter as the local or short-circuit currents, to distinguish them from the useful or work currents of the armature.

As an armature coil carrying current in a given direction, approaches and passes under the brush, the current should die

down to zero value at the midpoint of the brush and should rise to full value in the opposite direction by the time the coil leaves the brush. This would be a theoretically perfect condition, but is very difficult or almost impossible to attain in practice. The coil, while under the brush, has an e. m. f. generated in it due to cutting the armature field, as already described, and a local current circulates. This short-circuit current normally adds to that of the work current before reversal, and thus tends to maintain it right up to the moment that the coil passes out from under the brush. The reversal of the current in the short-circuited coil is thus accomplished almost instantaneously instead of gradually. If, however, this local current could be generated *in the opposite direction*, then it would tend to oppose the work current as the coil came under the brush, so that the *resultant current* would first die to zero and then rise in the opposite direction, if the short-circuit current were just large enough; so that the *work current would simply replace the short-circuit current in direction and value as the coil passes out from under the brush.* Therefore, if the short-circuit current were of exactly the right value, the resultant effect would be the same as if the work current alone were present and this current died down to zero value as the coil passed the middle of the brush, and rose to full value in the opposite direction by the time the coil left the brush. In other words, a local current *of the proper direction and value* in the commutated coils will give theoretically ideal commutation. Such local current therefore, might be designated as the *commutating current.* In practice it is found however, that a current somewhat higher than the ideal value gives the best general results as will be explained later. In any case, however, this local current, to be effective, must be in the reverse direction to that which would normally be set up by the armature coil cutting the magnetic field due to the armature winding itself. This means therefore, that where commutation is accomplished by means of short circuit or local current, an external field *in the opposite direction to the armature field is necessary* for setting up such local currents. This result may be accomplished in several ways. The brush may be rocked forward or backward until the commutated coil comes under the magnetic field, or fringe of the field, set up by the main field winding. If rocked in one direction (forward in the generator, backward in the motor) the direction of the main field will be in opposition to the armature field. Obviously, if shifted into a

strong enough external field, the armature field may be completely neutralized at some given point, such as that of the short-circuited coil, or the resultant field might be even strong enough in the opposite direction to set up the desired local or short-circuit current in the commutated coil. Under this condition, ideal commutating conditions should be obtained. However, as the armature magnetic field at this point tends to vary with the armature current, while the external field tends to remain constant, it is evident that the ideal resultant field will only obtain at one particular load. Therefore, only an average condition can be obtained in this way. However, by shifting the brushes backward or forward under the external field, the proper local or commutating currents should be obtained for any given load; but brush shifting is not usually considered a very practical method of operation, although required by many non-commutating pole machines in service. What is needed is an external field directly over the commutated coils which is always of the proper strength to set up commutating currents of the right direction and of the proper value with respect to the work currents, so that the resultant in the short-circuited coil will give the effect of the work current reversing at the middle of the brush at all loads. To accomplish this, an external field to produce this local current should always be in opposition to the armature magnetic field, should be somewhat greater in value, and should vary in proportion to the armature field,—that is, to the armature current. This result is accomplished by the now well-known commutating pole, which is simply a small pole placed over the commutated coil, and usually excited by a winding directly in series with the armature, but having a somewhat greater magnetizing force than the armature winding. The function of this pole is solely to set up in the armature coil a local or commutating current of the proper direction and value.

A condition which makes the problem of commutation very much easier to solve is the use of a relatively high resistance in the short-circuited path of the coil which is being commutated. Due to the extremely low resistance of the ordinary armature coil, a relatively low magnetic field set up by the armature would generate enormous local currents in the short-circuited coil if the resistance of the coil itself were the only limit. These currents might be ten to twenty times as great as the normal work current, and would add seriously to the difficulties of commutation. Even if a commut-

ating field were present, this would have to be proportioned and adjusted so accurately, to get the right value of the commutating current, that the construction would be almost impracticable. But if considerable resistance, compared with the coil itself, could be interposed in the short circuited path, this obviously would so greatly assist in fixing the value of the short-circuit current that undue refinement and adjustment would not be necessitated. Let us suppose, for instance, that the short circuit e. m. f. in the commutated coil is two volts, and a copper brush of practically zero resistance at the contact is used, then the resistance of the short-circuited coil itself limits the current which flows. Let us assume that this gives a local current of ten times the value of the work current. Now, if, instead of the zero resistance brush contact, one of about ten times the resistance of the coil is used, then the total resistance in circuit becomes over ten times as great, and the short-circuit current is cut down to a value comparable with that of the work current. Obviously this in itself would represent an easier condition of reversal without any external reversing field, and, with such a field, extreme accuracy in proportions and adjustment are not necessary to give approximately the right value of the local current which assists in commutation. Therefore, a relatively high resistance brush,—that is, one with contact resistance high compared with the resistance of the coil—is of very material aid in commutation. This is wherein the carbon brush is such a successful, or even necessary adjunct of the commutating machine. It serves such a vital purpose that it may be said that, without the carbon brush or its equivalent, the electrical industry would never have made anything like the progress it has made.

The principal function of the carbon brush being that of limiting the local current, it might be assumed that the advantages might be increased indefinitely by further increasing the resistance, but there are usually limits to all good things. The carbon brush increases the resistance in the path of the local currents, but it also increases it in the path of the work current. If the resistance is carried too high, the losses due to the work current may constitute a more serious objection than the local currents. Consequently, practice is one continual compromise on this point. In those cases where the short-circuit current is normally relatively small due to low value of the armature magnetic field, it is obvious that a lower resistance in the short-circuit

path can be used, or, in other words, a low resistance carbon brush is practicable, with consequent low loss due to work current. In other cases with higher inherent local current, higher resistance carbon will give better average results. It is thus obvious that one grade of carbon brush is not the best one for different machines unless they all have similar inherent commutating conditions. It is exceedingly difficult to give equal commutating characteristics to machines of different sizes and types, and, in most cases, even of the same type or line. In non-commutating pole machines, the grade of the brush is of more importance than in the commutating pole type, for in the latter, we have a means, in the commutating pole strength itself, of modifying or controlling the value of the local current. But the best commutating pole gives only average correction,—that is, average

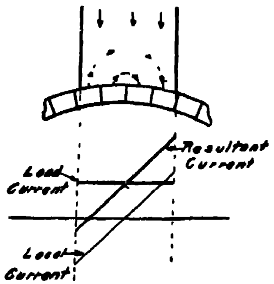


Fig. 3.

value of the desired local current, and the resistance of the brush must be depended upon to take care of pulsations or irregularities in the local current, acting to smooth them out to a greater or less extent. Thus a fairly high resistance brush is required on the commutating pole machine, but its resistance usually can be lower than that required in the non-commutating pole type.

The above gives a crude idea of the phenomena of commutation. However, there are a number of very closely related conditions, such as burning and blackening of the commutator, causes and effects of high mica, effect of under-cutting of mica, rapid and undue wear of commutator copper and brushes, etc., which can be explained more or less directly by the above theory.

Blackening of the commutator, high mica, and rapid wear of the commutator copper and brushes may all be credited to actual burning, or something similar to electrolytic action, occurring under

the brushes. It is not usually the bright sparks at the brush tips which cause trouble, but it is frequently on unnoted sparking under the brush face. These sparks may be very minute,—so much so that they would naturally be assumed to be harmless. The apparent electrolytic action under the brushes may be really a similar sparking action which cannot be observed. Experience has shown that usually there is a tendency for minute particles of the conducting material to be burned or carried away from the contact surfaces, (Fig. 3) depending on the direction of the current. These particles appear to travel in the direction the current is flowing, but they do not always deposit on the opposite contact surface. If the current is from the brush to the commutator copper, the brush surface tends to be eaten away, while with the current from the copper to the brush, the copper eats or burns away.

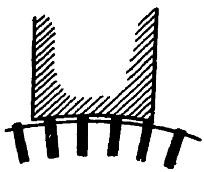


Fig. 4.

With ordinary current densities and very low loss in the brush contact, this action seems to be very minute, but it appears to in crease rapidly with increased loss at the brush contact. Therefore, high current density in the brush contact may produce this action. This does not mean high density due to the work current alone, but means the *high actual density*, due to both work and local currents. In non-commutating pole machines and in commutating pole machines with bad adjustment, the local current under the brush may exceed in value the work current. As this adds to the work current at one edge of the brush and subtracts at the other edge, the result will be greatly increased density and high watts under one part of the brush. This may result in burning away one edge of the brush surface, and is frequently observed in examination of brushes. This usually is most noticeable where the current passes from the brush to the commutator, but at the holders of the other polarity, a similar action is tending to burn away the commutator copper. However, the commutator mica does not tend to burn away, and there-

fore, if the mica does not *wear down mechanically* at the same rate that the copper burns away, eventually the mica stands an infinitestimal amount above the copper (Fig. 4) and the brushes will make a decreasingly good contact with the copper itself. This increases the loss at the brush contact and increases the burning action which results in still poorer contact, so that the results become cumulatively worse. If, however, these periods of burning are intermittent, due to variable load conditions, and there is considerable operation at lighter loads or non-burning conditions, the mica may wear down somewhat and the commutator and brushes may polish sufficiently during these periods to mask the direct effects of the burning. But the results may show in grooving and apparent rapid wear of the commutator face. There may thus be burning without blackening, or without direct evi-

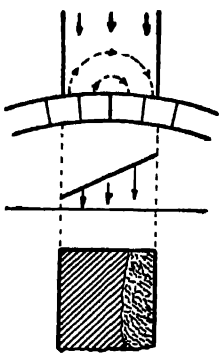


Fig. 5.

dence of high mica. If, however, the burning periods exceed the polishing, then visible evidence of burning and high mica may be found. The brushes may also show this burning and, in some cases, may honey-comb badly at one edge, or even over the whole surface. Where one edge burns over a very distinct area, (Fig. 5) it usually may be assumed that the burnt area could just as well be cut away, with but little harm to the operation, and possibly some good, for the fewer the commutator bars that the brush spans the lower will be the total short-circuit current, as a rule. And, moreover, by doing away with the localized burning under the brush, it may be assumed that the commutator burns less also. However, cutting away part of the brush face will crowd the work current into the remaining portion, so that burning in this portion

may be increased. Therefore, narrowing the brush face is not a general remedy for the trouble, but is successful in some cases.

Burning of the commutator may also be coincident with a deposit of copper on the brush face. This is usually known as "picking up copper." Apparently, in some cases, where the copper is burnt away from the commutator face, it actually collects or deposits on the brush face, forming low resistance spots or surfaces. This gives the equivalent of low resistance brushes, with consequent increase in local current and still greater burning action. Moreover, with several brushes in parallel, any one brush with copper on its face, may tend to take more than its share of the total work current, which tends to cause further heating and burning. Increased heating in itself will cause a greater tendency of the brush to take an undue proportion of the current, for carbon brushes, unfortunately, have a negative coefficient of resistance. This means that if any brush carries more than its share of current and becomes heated thereby, its resistance is reduced and it tends to take still greater current. This is particularly the case with a large current per brush arm, with a large number of brushes in parallel on each arm. If one brush, for any reason, such as picking up copper, takes an undue share of the current, it may take an increasing share until the contact surface, or the whole commutator end of the brush, may become red hot and slowly disintegrate. Such action, if continued, will eventually so destroy or injure the brush contact that it carries a decreased current, the resistance increases, and eventually the current falls, not only to normal, but probably far below normal value, due to bad contact, and the other brushes must then assume an excess. If other brushes repeat this action, then the conditions become increasingly bad for the remaining brushes, and they may repeat the same action. In time, all the brushes may thus become badly burned or honey-combed.

Such conditions are sometimes very difficult to correct. In some instances, higher resistance brushes bring improvement, while in other cases, lower resistance brushes are better. If, for instance, the local currents are relatively small, and the burning or picking up of the copper is due principally to the work current, then a lower resistance brush may actually reduce the watts at the contact, even though the local current may be in creased. If, on the other hand, the local currents are high and are principally responsible for the burning action, then a still

higher resistance may actually reduce the loss. Thus it may be seen that, in many of these commutator and brush problems, it is impossible to make a definite statement regarding the effect of any given make of brush unless one knows what is actually taking place in the machine. And every time the brush is changed, the conditions change, for they are more or less inter-dependent.

Another remedy for some of the above troubles is undercutting the mica between commutator bars. This does not remove the primary cause of the trouble, namely, the large local currents or high current density on the brush contact, but it lessens the harmful effect of these by allowing the brush to maintain better contact with the commutator copper, thus reducing the contact losses. In this way the burning action can be diminished, in most cases, to such an extent that the commutator face will polish, and this in turn will enable the brush to make better contact with the copper. Undercutting in general is advantageous where the commutator mica takes up a large percent of the total surface, such as 20% or more. The larger the percentage of mica, the less liable it is to wear away as rapidly as the copper, and the greater the liability of the brushes being lifted above the copper, with consequent burning and blackening. Not only must the percentage of mica be relatively small, but the actual thickness between two adjacent bars must also be limited, unless the mica is undercut. The general practice at present with non-undercut commutators is about 1-32 in. thickness between bars; and even considerably less than this, as low as .018″ to .020″ is not unusual in small machines which are not undercut. Where commutators are undercut, there is a possibility, or liability, of carbon dust collecting in the slots and short-circuiting between bars, unless the peripheral speed of the commutator is sufficient to keep the slots clear. Therefore, in slow speed commutators which are undercut, it may be necessary at times to brush out or clean the slots. In high speed commutators, or in variable speed machines which intermittently reach high speeds, there is usually but little difficulty from carbon collecting in the slots. Obviously, where a commutator is to be slotted, there is no necessity for maintaining a minimum thickness of mica, as the limitation in such cases is in the width of the slot, which may be as much as 1-16 in. in some cases. Wide slotting, however, is liable to produce brush chattering in some cases.

Slotted commutators, while advantageous in some ways, present certain operating objections in others. Except where the brushes cover several bars, the slotted commutators are liable to produce more or less chattering of the brushes, unless frequently lubricated. Therefore, with such commutators, self-lubricating brushes are recommended. Such brushes usually contain, or consist of graphite, and, in consequence, generally they are of lower resistance than ordinary carbon brushes, and therefore are not as useful in assisting commutation. In commutation pole machines where the resistance of the brushes is of relatively less importance, graphite brushes are often very satisfactory. As such brushes are usually soft in texture, they are not well adapted for wearing away the mica in commutators which are not undercut.

In the application of the commutating pole to direct-current machines, certain conditions have arisen which are peculiar to this construction. For instance, according to the theory already given above, the flux of the commutating pole should rise and fall directly in proportion to the armature current. This means that there must be practically no saturation in the commutating pole circuit. Probably many of the early difficulties with commutating pole machines were due to a lack of appreciation of this point. Also, in machines with rapidly changing current, the commutating pole flux should change *at the same rate* as the armature current or the proper local current conditions for commutation are not obtained. This means that the commutating field winding should not be adjusted or varied in strength by means of a non-inductive shunt, as is common practice in adjusting series field winding. As the commutating pole winding is normally inductive, then in the case of sudden change in current, an improper proportion of the current will flow through a non-inductive shunt at the time that the armature current is changing. Either no shunt should be used, or, if one is necessary, it should have the same inductance as the commutating field circuit. The former is preferable but requires most accurate designing.

Another requirement in commutating pole machines, is accurate setting of the brushes. As a certain definite value of the local or commutating current is desired in the short-circuited coil, it is obvious that the coil must be short-circuited by the brushes at some very definite position with respect to the com-

mutating pole. This is especially true in reversing machines. Otherwise, the commutation in the two directions would not be alike. Furthermore, an incorrect setting of the brushes, with respect to the commutating pole, will have a slight effect on the inherent regulation of the machine. In a direct-current generator, for instance, with the brushes set so that commutation is exactly central to the commutation pole, the magnetic flux of these poles has no resultant effect on the generated e. m. f. of the armature winding as a whole, and therefore has no effect on the regulation. But if the brushes are shifted ahead of this correct point in a gener-

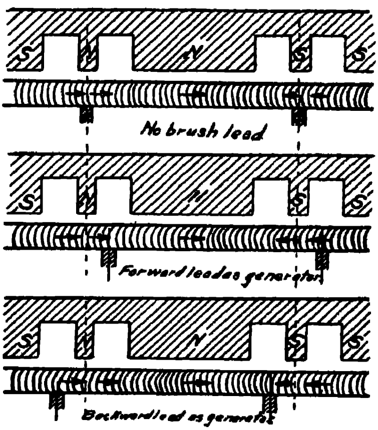


Fig. 6.

ator, (Fig. 6) part of the commutating pole flux becomes effective in generating e. m. f., and in *opposition* to the armature e. m. f. A back lead in the same way would tend to increase the armature e. m. f. Thus the inherent regulation of the generator is affected by the brush setting. In a motor with commutating poles, a forward lead of the brushes tends to increase the counter e. m. f. generated and thus tends to lower the speed with increase in load, while a back lead tends to increase the speed. With perfect setting of the brushes with respect to the commutating poles, and an adjustment of the commutating pole strength just sufficient to give the theoretically ideal short circuit or commutating current, the commutating poles should have practically no effect on the speed. But in actual practice, in direct-current motors, it is found better to actually over-compensate

slightly—that is, to make the commutating pole slightly stronger than the ideal value. This increases the local or commutating current above the ideal value so that commutation is well completed before the coil leaves the brush. This gives less sparking, or "blacker" commutation, at the brush edge, and apparently is more satisfactory from the operator's standpoint. But this over-compensation has an effect on the speed characteristics of a motor. It means that the zero point of the current is shifted backwards, and the resultant effect is similar to shifting the brushes backwards, and it therefore tends to speed up the machine, as described before. But this speeding-up tendency will vary with the load, as the commutating pole strength increases with the load. If the motor normally has a "flat" speed curve, this increase may be sufficient to bring the speed with load above the no-load speed, and this is an unstable condition in the operation of constant speed motors. For instance, if a motor with rising speed characteristics has a high inertia load suddenly thrown on it, the heavy current required will tend to speed up the machine, and thus take a still heavier current. But a drooping speed curve has the opposite effect. Therefore, in motors built for general market conditions, where the load conditions may be of any nature, it is desirable that so-called constant speed motors should always have slightly drooping speed characteristics at least. But commutating pole motors, if designed along ideal lines,—that is with high armature magnetomotive forces—and with comparatively flat inherent speed characteristics, are liable to be affected, in speed, to a certain extent, by overcompensation of the commutating pole. In some cases, this effect may be so small that it does not over-balance the inherent droop in the speed curve. In other cases, it may more than over-balance, so that the actual speed curve rises with load. This is particularly noticeable in adjustable speed machines for a wide range in speed. Such machines have full field strength at lowest speed, and here the effect of the local or commutating current on the speed may be very small. At three or four times speed, however, the main field is very weak, while the commutating current is practically the same as at low speed, and therefore has three or four times the effect in increasing the speed.

Therefore, such motors are liable to have rising speed curves at higher speeds, although they may be slightly drooping at the lowest speeds.

Obviously, as this effect is a function of the armature current, it should be corrected by means of the armature current. This is readily accomplished by adding to the main field winding a very small winding in series with the armature, and connected to magnetize in the same direction as the shunt winding on the field poles. While this might be looked upon as a series winding, yet its function is that of compensation for commutating pole action. The ampere turns in this compensating winding are normally very small, being just sufficient to balance the effect of the excess short circuit current in the commutated armature coils. In adjustable speed machines, at low speed and full field strength, this small compensating winding has but very little effect, as it is so small in proportion to the shunt ampere turns. At the highest speeds, however, where the shunt ampere turns are very low and the rise in the speed curve is liable to be greatest, this compensating winding has the most effect. It therefore tends to produce proper compensation at all speeds and loads.

Another phenomenon which has appeared in direct current machines, and which, at times, has been falsely credited to commutating conditions, is that of "pitting," or "eating away" of the mica between commutator bars. Nearly all manufacturers and operators have encountered this difficulty at some time or other. This has also been credited to high voltage between bars, too thin mica, quality of carbon brush, use of lubricants, etc. Some years ago, the writer and his associates made an extended study of this matter, based upon a very large number of cases of actual trouble. The results which were derived from the general practical data from machines in actual service were so conflicting that no positive conclusions could be drawn directly from such data. However, eventually the evidence pointed to oil as apparently one of the fundamental conditions in this trouble. Extended tests were then made to determine the effects of oil on the mica, and the results indicated very clearly that those insulations which absorb oil were liable to pit or eat away in time. Apparently where the oil could dissolve out the binding material in the mica, minute particles of carbon or copper would be disseminated through the mica, thus decreasing its resistance locally. Combustion of these particles would usually be noticed as "ringfire" around the commutator. Ring-fire is almost always due to incandescent carbon particles scraped off the brushes,

but is not usually harmful if the mica adjacent to the spark does not burn or deteriorate. Experience shows that the ordinary good grades of mica plate are not affected by such ring-fire, and it is only when foreign conducting particles penetrate into the plate that this burning may gradually eat away the mica. It was found that some binding materials used in building mica-plate were much more soluble in oil than others, and it was noted that in those plates with soluble binders, the pitting was most pronounced. In fact, in those grades of mica plate, where the binder was practically insoluble in oils, no pitting was found, even under very extreme conditions of test This led then to one solution of the pitting trouble, namely, the use of what might be designated as insoluble binders in the mica plate, with very tight construction of commutator, so that oil could not penetrate along the sides of the plate, and with care in preventing oil from getting on the commutator. With the first two conditions, the latter should not be so important, yet one never knows whether the first two conditions are perfect, especially after a machine has been in operation for a long period and has been subjected to severe changes in temperature at the commutator.

After getting at the probability of oil as a cause of pitting, many careful examinations were made of pitted mica, and in general, there was evidence that the mica binder had been attacked by oil. In some instances where the operators were absolutely sure that there had never been any oil on the commutator, careful chemical and microscopical analysis showed the oil. In some cases the mica was actually spongy with oil, and yet it was claimed that no evidence of oil had ever been noticed on the commutator.

Much depends upon the grade of mica used in the plate for building up in commutators. Certain micas seem to wear much faster than others, and yet be just as good insulators. The well known amber micas seem to be by far the most successful for this purpose. Many attempts have been made to use cheaper grades of white mica, and, in some cases, with good success, but the difficulty is that it is not uniformly successful, and trouble from high mica may develop only after a large number of machines have been put on the market. Many costly experiences of this sort have made the manufacturers very conservative in this matter. It takes so long to find whether a new mica is good

or not, that it is questionable in most cases whether it should be tried out at all.

In the early days, the commutator mica was made comparatively thick, and was punched out of solid material. When the slotted types of direct current armatures came into use, with their greater sparking tendencies, the old solid thick mica, used with surface-wound armatures, immediately showed trouble due to high mica. This soon led to thinner mica, which helped the trouble somewhat. Then somebody discovered that, by splitting the mica into very thin plate and reassembling, without binder, the results were still better, as this split-up mica seemed to wear or flake off at the edges much better than solid mica. Then someone discovered that still better results were obtained by splitting or flaking the mica and building up into plates, with a suitable binder Since that time, practically no radical improvements have been made in commutator mica, except in the binding material possibly, and in the better choice of the grades of mica used, but the mica-plate of today in general is very similar to the mica-plate of 15 or 20 years ago. Of course, refinements in manufacture have occurred, which, in most cases, however, have had but little effect on the quality of the product. At present, it does not look as if a more suitable material can be found for this purpose Many attempts have been made to substitute other materials, but these have only proved successful in certain applications. The built-up mica possesses certain physical qualifications which have not been obtained with any other material. For instance, under heating and cooling, the commutator changes in dimensions circumferentially, as well as axially, and under this action the mica undergoes much more compression at times than at others. Therefore, a material of a more or less elastic nature is required between bars, in order to avoid permanent compression, with resulting eventual looseness. Structurally the mica-plate meets this condition very well. In the second place, the material between bars should be one which wears down properly and yet does not have any cutting or grinding action on the commutator and brushes as it wears off. Mica apparently meets this condition, while many other mineral compounds, such as asbestos, appear to have a grinding action. In the third place, the material should be more or less heat and spark-resisting. Again, it should be a non-absorbent of oil. Well-built mica-plate seems to be the only material so far which

meets all the requirements for general purposes. Hard, inelastic materials of various sorts have been tried and have not proved successful. Asbestos in sheets and plates and in conjunction with other materials, has not proved very satisfactory. Fibrous and cellulose materials have given good results in some cases, but are not sufficiently heat and oil-proof for general purposes. The only material departure has been made in micas used with undercut commutators. In such cases, white micas and others which have all the good characteristics of the amber micas, except their wearing characteristics, can be used, for the undercutting eliminates the necessity for good wearing qualities. At the same time, undercutting, as explained before, is advantageous in other ways.

There are a number of mechanical conditions entering into the practical side of the problem of commutation. As shown before, it is very important to maintain good contact between the brush face and the commutator in order to keep down losses and burning action. Moreover, good contact in general should mean good contact *over the whole brush face* in order to keep down the current density. Therefore, if the brushes chatter or vibrate in their holders, or have a rocking action tending to give alternate "heel-and-toe" contact, obviously the operation is liable to be affected thereby. Vibrating brush holders, vibrating brushes and chattering or movements of any kind with respect to the commutator face, are objectionable and, not infrequently, very harmful.

Vibrating brush holders may be due to various causes, which do not show up on the manufacturer's test. The machine may be so located that its environments are to blame for vibration. Bad gearing may cause chattering. The foundations or supports may not be as substantial as on the shop test, so that some small disturbance may be exaggerated and produce vibrations in parts or in the whole machine. Sometimes the brushes may chatter due to lack of lubricant, and this may set the whole brush holder structure into vibration. Whatever the cause, it is always best to stop such vibrations as far as possible, especially in machines handling large currents.

Vibration of brushes in their boxes may be due to badly fitted brushes, (Fig. 7) or, on machines which have long been in operation with heavy currents per brush, the brush boxes may be eaten away inside so that they are not of uniform di-

mensions. Low resistance shunts on carbon brushes are for the purpose of carrying away the current from the brush by some other path than through the sides of the brush box. However, due to the raking or dragging action of the commutator on the brushes, they are liable to bear rather heavily against one side of the box, especially at the lower edge next to the commutator. Some current will naturally pass to the box, and this in time will tend to burn away the boxes and the carbons. However, as the carbons burn away, they are eventually replaced by new ones; but the boxes are seldom replaced, and in time they may burn away so that they are larger next to the commutator. The brush then fits tightly only at the top and is free to move or vibrate or chatter at the commutator end, which is just the place where such movement should be avoided. Attention is called to this action in particular on account of the carelessness often exhibited in regard to the shunts on the brushes.

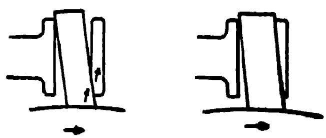


Fig. 7.

Chattering is not infrequently due to lack of lubrication on the commutator or in the brushes. When the commutator gets too dry and has a high polish, a radial, or almost radial brush may vibrate or chatter just as a pencil does when moved along a pane of glass. If the commutator is lubricated with oil to overcome this, care should be taken not to use an excess of oil or the mica may absorb it. Frequently immediately after oiling, a commutator shows ring-fire, which is due to combustion of minute particles of carbon and oil over the top of the mica. Sometimes chattering is best overcome by the use of self-lubricating brushes. In undercut commutators, the slots are liable to cause chattering with non-lubricated brushes, giving out a noise of a pitch comparable with the product of the revolutions by the number of commutator bars. As oil-lubrication should be used with caution on undercut machines, practice now usually calls for some form of self-lubricating brush, partly or wholly graphite, as has been referred to under "under-cutting."

In communicating pole machines it is especially important that the brushes should not have any heel-and-toe movement,

for when the brush makes contact at one edge or the other, the result is equivalent to rocking the brushes backward or forward, which, as explained before, is particularly objectionable in such machines.

In direct-current machines, burnt or black spots will sometimes develop on the commutator at points removed from each other a distance corresponding to that between holders of the same polarity. This is sometimes very bothersome, and the cause of the difficulty is not always easy to find. Any condition which produces one bad spot may tend to produce similar spots symmetrically displaced around the commutator. When one spot is formed, and this spot passes under one brush arm, the brush contacts at this arm are naturally poorer and the other brush arms of the same polarity tend to take the load, and the current density in their brushes is correspondingly increased during this short period. If there is any tendency toward high mica, for instance, then the increased current at these points will produce increased burning away of the copper and burnt spots may develop. If once developed they may gradually travel around the commutator until the whole commutator is black. A local or high mica strip may be the initial cause of the trouble, or a rough spot on the commutator may give the same result. But very often, resultant high mica, following the initial cause, tends to spread the trouble. As soon as such black spots are noted, further trouble frequently can be headed off by scraping or cutting the mica below the copper surface in the burnt regions.

One of the most severe conditions that any direct-current generator can encounter is a dead short-circuit across its terminals, or in the immediate neighborhood of the machine. Very few machines outside of those of comparatively small capacity and of low voltage, can stand such short-circuit without severe flashing. Tests have shown that moderately large direct-current generators will give, at the moment of short-circuit, from 20 to 30 times full load current. No ordinary commutating machine can be built to take care of such a current rush, and vicious arcing and flashing generally results. This is an inherent condition in the design. No responsible manufacturer who knows his business will guarantee to overcome this characteristic. However, fortunately, the great majority of short-circuits on direct-current power systems occur at some distance from the generator, and moreover, in many cases, such short-circuits are made

through arcs rather than by dead contact, so that the generators do not get the maximum possible current rush.

It might be suggested that quick-acting circuit breakers would take care of such extreme conditions by opening at the loads for which they are set. But this setting is that at which the tripping mechanism works, and if the current rises rapidly enough, it may be far in excess of the tripping value by the time that the breaker actually opens or ruptures the circuit. In fact, this is just what happens in the case of a severe short-circuit. Oscillograph tests have shown that the current "rush" on short-circuit may reach its maximum value in one-fiftieth of a second, or even less, while the ordinary commercial circuit breakers seldom operate in less than one-tenth of a second, which, in reality, is pretty rapid action for a mechanical device Therefore, it will have to be an extremely rapid-acting breaker which can get the circuit open before the short-circuit current has risen to several times the full load value.

One other subject might be considered under commutation, namely, the influence of the commutating characteristics upon the permissible range of speed variation and speed adjustment in direct-current motors. There are two general methods for obtaining speed variation in such apparatus, namely, by variation in the e. m. f. supplied to the armature terminals, and by variation in the field strength or flux.

In the early development of adjustable speed motors, the first of the above methods was used almost exclusively, largely on account of the fact that the commutation problem was more easily handled with this method. As the motor could be given full field strength much of the time, and as the reduction in field strength was not great under any conditions, fairly good commutation was obtainable in general. Where constant torque was required, this method was fairly satisfactory and economical However, where constant horse-power was required, obviously, with this method, the armature current had to be increased directly as the armature voltage and speed were reduced. Thus the armature had to be designed for a voltage capacity corresponding to the highest voltage, and a current capacity corresponding to the lowest voltage. Thus it became quite large for a given horse-power rating, and was therefore very uneconomical in material. However, the larger currents at lower voltages did not represent such a hardship in commutation, for these increases in current

were accompanied by corresponding reductions in speed, which made commutating conditions proportionately easier. Thus the commutating problem was not so serious with this method of speed control. However, for constant horse-power service, it was obvious, early in the development, that the most economical arrangement as regards material, would be the use of a constant voltage across the armature, thus requiring constant armature current, speed control being obtained by variation in the field strength. But this meant that the field had its full strength at the lowest speed, and the field flux would be decreased directly as the speed was increased. This was the ideal arrangement, but, unfortunately, commutating conditions were very difficult at the weaker fields,—that is, at the higher speeds. In consequence, a number of more or less freakish designs were put out, with the idea of overcoming the commutation troubles, by using variable field speed control. Some of these designs were satisfactory from the operating standpoint, but this method of speed control did not reach its full development, except in the commutating pole type of machine, thus showing that the commutation problem was a serious one in this method of operation. With properly proportioned commutating poles, the commutating conditions are practically independent of the speed, so that, with their use, the real limitations in speed range are found in other conditions, such as the instability of very weak fields, etc.

It is evident from the above that, as regards speed regulation in direct-current work, a constant field motor is at a serious disadvantage compared with one in which the field strength can be varied. In fact, this holds true for alternating-current as well as for direct-current motors, as will be shown later. The alternating-current induction motor is essentially a constant field machine, and normally operates at constant speed, on a given frequency. In the constant field direct-current motor, it was shown that speed variation is accomplished by variation in the voltage applied to the armature. The analogous condition in the induction motor would be in variation in the frequency applied, and not in the voltage. This, then leads up to the next subject, namely;

Speed Control of Induction Motors

Repeating preceding statements, the induction motor is primarily a constant speed machine when supplied with constant frequency and e. m. f., which is the standard condition in all

alternating power service. When running at full speed, the secondary frequency and e. m. f. are both very small, the frequency being only such as will generate enough e. m. f. to send the required secondary currents through their own windings when closed upon themselves. If the secondary resistance is increased, with a given current flowing, the secondary e. m. f. must be proportionately increased, and the secondary frequency, to generate such e. m. f., must also be correspondingly increased. This secondary frequency, which represents the departure from synchronous speed, or the "slip," is therefore always proportional to the secondary e. m. f. Therefore, speed regulation of the motor, by means of the secondary circuit, means corresponding, or proportional variation in the secondary frequency and e. m. f., and all methods of speed regulation or adjustment of induction motors through secondary control are based upon frequency and voltage variation in the secondary circuits.

All methods of speed regulation of induction motors may be classified under two general heads; (1) primary circuit control, and (2) secondary circuit control.

Primary Circuit Control

Two general methods are practicable, namely, variation in the number of primary poles, and variation in the frequency supplied to the primary. The former method is very limited in the range of control which is practicable. Usually, two operating speeds can readily be obtained, while three or four lead to much added complication, and more than four speeds does not appear to be commercially practicable except in very special cases. For fine graduations in speed, pole changing is apparently out of the question.

By suitable change in the primary frequency supplied to the motor, any desired speed, or speed range, is obtainable. But in general, the problem of furnishing this variable frequency is just as serious as that of speed adjustment of the motor itself on a fixed frequency. In other words, it takes the difficulty away from the motor and transfers it elsewhere, but does not eliminate it.

There are various ways of generating variable frequency. For instance, an alternator may be driven by an adjustable speed motor. This should be a direct-current motor, for, if an alternating motor is used, the problem of varying its speed is just the same as that of the induction motor which is to be regulated.

Another way is to connect the alternating-current generator to an adjustable speed prime mover, such as an engine or waterwheel. Such methods of regulation require one generating outfit for each motor to be regulated, except where two or more motors are to be regulated over the same range at the same time The method in general is very seldom used.

Other possible methods of regulating the primary frequency lie in frequency changers of certain types by which a given frequency can be converted to any other frequency by commutation of alternating current. Various types of such machines are possible but they possess certain very objectionable limitations, in that they must commutate currents of frequencies approximating those of the primary supply system At 25 cycles, this may be practicable, in some cases, but on 60 cycle supply circuits it is out of the question. One other serious objection to regulating the primary frequency is that the frequency controlling device must have a capacity equal to that of the motor to be regulated,—that is, the entire input of the induction motor must be handled by the frequency regulator.

In general, therefore, regulation of induction motor speed by change in primary frequency is not advisable, and appears to be practicable only in certain very special applications. This then brings us to the alternative of secondary circuit control.

Speed Control by Change in Secondary Frequency

As brought out before, any speed variation of an induction motor with unchanged primary frequency means accompanying change in the secondary frequency and voltage. At standstill, the secondary voltage is a maximum, and the secondary frequency is 100 percent of that of the primary,—that is, it is the same as the primary. At true synchronous speed, the secondary voltage and frequency are zero. At any intermediate speed, the secondary voltage generated and the secondary frequency are respectively equal to the standstill voltage, and the standstill or primary frequency, multiplied by the slip, in percent, the slip being the drop from synchronous speed. It should be noted that the secondary generated voltage is mentioned, for this is not the same as the secondary terminal voltage, due to a certain internal drop in the windings when current is flowing. This internal drop is usually small compared with the secondary standstill voltage, usually being from 2 percent to 3 percent except in small motors, and

therefore may be neglected in any general discussion not involving exact calculations.

All methods of secondary circuit control in induction motors include some methods of regulating or controlling the secondary voltage and frequency. The simplest practical device is the use of resistance inserted in the secondary circuit. In order to get the required current, for a given torque, through such resistance, the voltage must be increased and this requires increase in the secondary frequency,—that is, drop in speed. But with a given resistance, if the load or torque is varied, the secondary current must vary, which means corresponding variation in voltage and secondary frequency,—that is, in speed. Therefore, speed regulations by secondary resistance means *variable* speed with variations in torque; and *constant* speed with variation in torque is only obtainable by varying the resistance inversely with the current, in order to obtain a *constant voltage drop*. Such method of speed regulation is therefore satisfactory only to a limited extent. Moreover, this method of speed regulation is uneconomical, in that there is a rheostatic loss practically proportional to the drop in speed below synchronism. At half speed, for instance, half the output of the motor is wasted in resistance.

Obviously what is needed is some arrangement which will absorb the required secondary voltage in other than resistance, and which will automatically hold such voltage constant, with varying current, in those cases where constant speed characteristics are required for each speed setting The difficulty in obtaining such a device is not simply in the voltage range required, but is largely on account of the range in frequency necessary. Therefore, all such devices must be of adjustable frequency, and therein lies the true difficulty, just as in the case of frequency changers in the primary circuit, as already referred to. The difficulty, however, is not nearly as serious in the case of regulation of the secondary circuit, for the variable frequency device needs to be of a total capacity corresponding to the slip, in percent. Furthermore, where the departure from synchronism is not large, the actual frequency in the frequency controlling machine is so low that commutator type alternating-current machines are permissible up to relatively high capacity. The problem therefore resolves itself into one of variable frequency, just as in the case of primary circuit regulation, as already referred to, except that the frequencies and capacities dealt with usually are very

much lower in the case of secondary circuit control The problem is simply easier, but not of a different nature.

In all methods of rating by secondary control, the regulating device must absorb power corresponding in percent practically to the secondary terminal voltage, or the secondary frequency, or slip. This power must be utilized if economical operation is required. There are three general methods by which it can be utilized, namely, it may be transformed to mechanical power and assist in driving the motor shaft, or it may be transformed to the primary or line frequency and fed back into the line, or it may be transformed to direct current for use in some other part of the system. Combinations of these three methods may be used. For instance, this secondary power may be transformed to direct current and then be transformed to mechanical power by means of a direct-current motor connected to the induction motor load. Or, it may be transformed to direct current and then re-transformed to the primary frequency and fed back into the line.

Three types of variable frequency devices have been proposed for absorbing the secondary terminal voltage, namely, A. C. commutator motors, rotary converters, and commutator type frequency changers. In the first named, the A. C. commutator motor either delivers its power directly to the shaft of the induction motor, or to an A. C. generator which returns it to the line, or to a D C. generator which delivers its current to some D. C. system or load where it can be utilized. In the second type mentioned, a rotary converter absorbs at its collector rings the secondary terminal voltage and transforms it to a proportional direct-current voltage. The direct-current power is then fed into a direct-current motor connected with the induction motor load, or is transformed to the primary frequency by a suitable motor-generator set. In the third type, a commutator type frequency changer transforms the secondary terminal voltage and frequency to a proportionate voltage at the primary frequency, and, by means of suitable transformers, the secondary power is then returned to the primary supply circuit.

Each of these arrangements possesses some advantages over the others, and also some disadvantages. The A. C. commutator motor is a relatively expensive type of machine, especially for very low speeds. Therefore, when the induction motor to be regulated is of comparatively low speed, placing the commutator

motor on the induction motor shaft means a relatively expensive commutator machine. In such cases, it may be advisable to either gear it to the load or connect it to a generator which returns power to the line or delivers it to another system. By such means, a smaller and higher speed commutator type A. C. motor may be used, but at a certain expense in auxiliary apparatus. For a frequency of 25 cycles, the A. C. commutator motor does not present any undue inherent difficulties if the speed range of the secondary control is not too large. With 50 percent drop in speed, for instance, the frequency handled by the A. C. commutator motor is only 12½ cycles. But with a 60 cycle supply system, a speed range of 50 percent means that the A. C. commutator motor must handle 30 cycles, which is a much more difficult and expensive proposition.

With the rotary converter speed regulation, no new or difficult problems are involved, either in the transformation or utilization of the secondary power. Where the induction motor speed is not too low, a direct-current motor connected to the shaft may utilize the direct-current power from the rotary converter. However, unlike the A. C. commutator scheme above described, the rotary converter arrangement makes its best showing in connection with 60 cycle supply systems, for, with the higher frequency, the secondary frequency of the main motor is correspondingly higher for the same speed range, which allows the use of a relatively smaller rotary for the same percentage of power transformed. To illustrate—On a 25 cycle supply system, with 30 percent speed range, the maximum secondary frequency is 7½ cycles. A 4-pole rotary operating at this frequency will run at 225 r.p.m.; that is, at this speed, it transforms or utilizes 30 percent of the power of the induction motor. Considering now, 60 cycles, with the same speed range, the secondary frequency becomes 18 cycles, and a 4-pole rotary of 30 percent of the motor capacity will operate at 540 r.p.m. on this frequency. Obviously, a rotary converter of much smaller dimensions can be used, than in the former case. The auxiliary means for absorbing the direct current power from the rotary converter can be practically the same for either frequency. Therefore, with this method, 60 cycles makes the better showing.

In the third scheme, (Fig. 8) the secondary frequency of the induction motor is transformed directly to the primary frequency in a single machine. The auxiliary means for utilizing the trans-

formed power consists of suitable stationary transformers with tap for varying the voltage. As the frequency changer is a rather unusual device, a brief description of its principle may not be out of place at this point. As usually built, it consists of an armature like that of a rotary converter, equipped with both commutator and collector rings. Unlike the rotary, the field may consist of a simple "keeper" or ring, (Fig. 9) without windings, which encircles the armature. Also, unlike the rotary con-

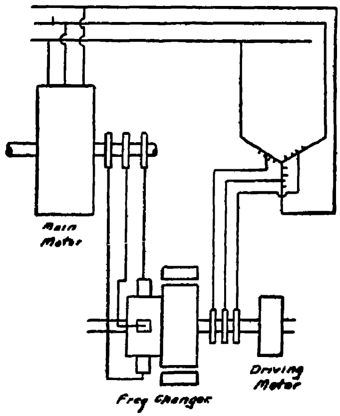


Fig. 8.

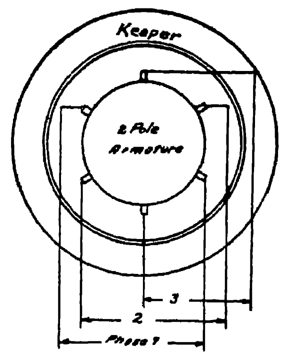


Fig. 9.

verter, the commutator is equipped with a double or triple set of brush holders for handling polyphase current. The ordinary spacing of the D. C. holders on a direct current rotary would correspond to one phase of the frequency changer. The armature can be driven by any suitable small-capacity, adjustable speed device. Practically the only load carried by the driving device consists of brush friction and windage.

If such a machine has its collector rings connected to the main supply system through suitable transformers, a rotating field will be set up in the armature core (and keeper) which travels around the core at a speed corresponding to the frequency divided by the number of poles, just as in an induction motor. If, now, the core is rotated mechanically in the opposite direction, at a speed equal to the frequency divided by the number of poles, then the magnetic field set up in the core will stand still in space and could be replaced by an external field excited by direct current,

just as in a rotary converter. Under this condition, the brushes on the commutator would tend to deliver current,—that is, alternating current having zero frequency. Under this condition, the external stationary keeper has zero frequency in it, while the armature core has normal frequency. Assume now that the core is rotated either faster or slower than synchronous speed. The magnetic field set up by the armature winding will travel backward or forward in space at speed corresponding to the departure of the core from synchronism and the brushes on the commutator will tend to deliver alternating current at a frequency proportional to the departure of the armature core from synchronous speed. Thus by varying the speed of the armature core from synchronism, any desired frequency can be obtained at the commutator brushes But the voltage at the commutator brushes is practically equal to the voltage at the collector rings, regardless of the speed of rotation, and by varying the voltage supplied to the collector rings, the voltage at the commutator can be varied independently of the frequency, which is dependent solely upon the spead of the armature. Thus, independent control of the voltage and frequency is obtainable, which makes the device quite flexible in its application. But such a device has other very desirable characteristics. As it is primarily one form of rotary converter, we should naturally expect that it would show some of the small-copper-loss characteristics of the rotary converter. Analysis, however, shows that it goes even further than this. In a 6-phase rotary converter, for instance, the armature copper loss averages about 26 percent of that of a corresponding direct-current winding, due to part of the alternating current being fed directly through to the direct-current circuit without transformation. But as there is transformation from one kind of current to another, the operation is incomplete, and there are certain transformation losses which are especially large at and near the so-called tap coils, which are connected to the collector rings. But in a 6-phase frequency changer of the above type, the transformation is from 6-phase alternating current to 6-phase current of another frequency, and a still larger percent of the current passes through without transformation than is the case in a 6-phase rotary converter. In consequence, the frequency changer has only about two-thirds as much copper loss as a rotary converter; that is, for 6-phase, it is less than 18 percent of that of a corresponding direct-current machine. Moreover, the tap-coil losses of the rotary converter are practically

absent. It thus becomes an extremely effective transforming device, as far as frequency is concerned.

Such a device is also very economical as regards iron losses. As it generates voltages, when connected to the secondary terminals of an induction motor, which are proportional to the speed range, obviously, with moderate speed variations, the magnetic flux in the armature core will be small compared with what would be necessary to generate full secondary voltage. Also, even this reduced induction is at a comparatively low frequency in the surrounding ring or keeper, and is only at full frequency in the armature core proper. Evidently therefore, the armature core and armature teeth sections can be made relatively small where the range of speed adjustment is small, such as 25 percent to 35 percent from synchronism. This small average core loss, together with the very small copper loss tends toward a very economical construction of machine.

In such a frequency changer, the problems of commutation are very similar to those in the A. C. commutator motor, and at 25 cycles the design becomes simpler and easier than at 60 cycles. The machine is independent of the speed of the induction motor to be controlled, which is not the case with the A. C. commutator motor in its simplest application, namely, direct connection to the main motor shaft. Such frequency changer in its simplest form may be arranged to be self-compensating, and the commutating conditions can be brought well within those of well-proportioned A. C. commutator motors.

In the application of these various speed regulating devices, two power conditions should be given consideration,—namely, whether the motor outfit is to develop constant horse power at the shaft, or constant torque, with the developed power varying in proportion to the speed. In most cases, in steel mill work, constant torque is all that is necessary, while in a few special cases constant horse power may be desired.

Where constant torque is preferred, the frequency converter should prove to be most desirable in many ways, particularly on account of its flexibility in application, so that a few suitable sizes should cover range of application. In this feature, and in a number of others, it has the advantage over the rotary converter or the alternating-current commutator motor schemes.

Where constant horse-power is required, it is questionable whether any one scheme has the advantage in all cases. Where

the induction motor speed is fairly high, and the frequency is low, the A. C. commutator motor directly connected to the induction motor shaft is a good arrangement, as only one regulating machine is required. If, however, the speed is so low that the A. C. commutator motor connection to the main shaft is inadvisable, so that power must be returned to the supply system, then this arrangement will not compare favorably with the frequency changer scheme. The rotary converter scheme, delivering direct-current power to a motor on the induction motor shaft, also makes a good constant power outfit, but where the speed is too low to allow an economically proportioned direct-current motor, the scheme is also at a disadvantage compared with the frequency changer. But where the frequency changer is used with constant horse-power, the main induction motor must be large enough to deliver the rated power to the shaft at the lowest speed, the excess power being transferred to the line by the frequency changer. If, however, the main motor is operated above synchronism at its highest speed, by an amount corresponding to the slip below synchronism at its lowest speed, then the increase in capacity of the main motor and of the frequency changer, to give constant power at the shaft, will be only about half as much as if all the speed variation were below synchronism. This brings up a point not yet brought out, namely, that some of these adjustable speed devices allow operation of the main motor above synchronous speed. This is particularly true in those cases where the speed-regulating or auxiliary apparatus can impress its own frequency upon the secondary of the main motor, and where such impressed frequency can be independently controlled. In such cases, by gradually varying the frequency down to zero and then up in the opposite direction, the main motor can have its speed varied through the synchronous position.

Various other methods of speed regulation have been proposed, but most of them have not yet seen actual test. Several schemes have been proposed for utilizing mercury vapor rectifiers for transforming the secondary current of the induction motor to direct current. This is one case where a frequency-changing controlling device does not form a fundamental part of the control. On the other hand, such method of control is as yet more theoretical than practical, and moreover, the mercury rectifier is not yet in general use for power service. At best, therefore, this method is one of the future.

Correction of power factor in induction motors, by means of a low frequency exciter in the secondary circuit is feasible. In connection with the above described adjustable-speed devices, it may be said that almost all such devices can be designed to correct power factor, as well as to produce change in speed, and, in many cases, this involves practically no extra complication. For instance, in the frequency changer method, where the voltage can be varied independently of the frequency, an increase in the frequency changer voltage without change in speed would simply mean the transfer of wattless current from the supply system to the secondary circuit of the induction motor, and this replaces the primary wattless magnetizing current. By proper voltage adjustment, the primary wattless component could be reduced to zero, or even changed to a large leading, instead of lagging, component, with consequent change in power factor from lagging to leading of any desired value. This simply illustrates the general method of power factor correction by all these various devices.

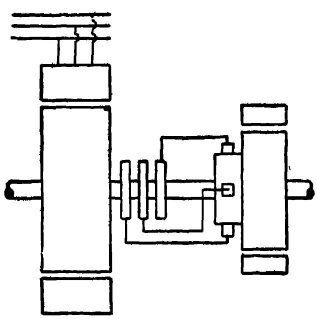


Fig. 10.

While on the subject of power factor correction, it may be stated that only two general methods of power factor correction are practicable—namely, by means of static condensers connected across the system, and by means of rotating condensers of some form. (Fig. 10).

The static type of condenser is commercial on a small scale, and, possibly, may become so on a large scale in the not far distant future. Large capacity static condensers can be built at present, but possibly not at a cost which will compete with the rotating type.

Rotating condensers may be divided into two sub-classes,—namely, synchronous and non-synchronous. The synchronous type is well known commercially. Usually it is simply a synchronous motor with over-excited field. It may or may not deliver power as a motor while acting as a condenser.

The non-synchronous condenser is simply a non-synchronous or induction motor with its secondary excited, instead of its primary. When acting as a condenser, the secondary is over-excited. It is therefore somewhat similar to the synchronous condenser, low frequency alternating current, instead of direct current being used for excitation. The condenser also may act as a motor delivering power. This type of condenser has not been used to any extent in this country.

From the foregoing discussion of speed control, it is apparent that the frequency of the supply system has an important bearing on the induction motor problem in general. There are only two accepted standard frequencies in general use in this country,—namely, 60 and 25 cycles, and both are in use in central power stations. The tendency for mills and factories to purchase power from such central power stations, instead of generating it themselves, appears to be increasing. This therefore, leads to another subject of direct interest to steel mill engineers, namely,—

Choice of Frequency

This question is not limited to mill work, but has become a very general one in the whole electrical business. Some years ago a committee of steel mill engineers decided upon 25 cycles as a standard frequency for steel mill work. The reasons for this decision were amply sufficient at that time and still hold good to a certain extent. But, in more recent times, the general tendency of the large central station or power companies toward 60 cycles, together with the sale of such power to steel mills and other industrial plants, has changed the situation somewhat. At the time that the steel mill committee recommended in favor of 25 cycles, there was an apparent tendency of the large power companies toward this frequency. But, as intimated, that tendency is now reversed, partly due to improvements in certain types of apparatus, such as rotary converters. It therefore may be pertinent to discuss this subject of frequency more fully, in view of its possible influence on mill work.

The principal loads to be handled by general power or central station alternating current plants are: first, lighting, including arc, incandescent, etc.; second, motor power service; and, third, direct-current service for various purposes, such as railway, etc.

In general, there is no particular question regarding the better frequency for lighting service, for 60 cycles, for direct use in both arc and incandescent lamps undoubtedly gives better results than 25 cycles.

When it comes to motors, either synchronous or induction, 60 cycles present more advantages in general, except for very low speeds, and, even in this case, with synchronous machines, the choice is in doubt. In the case of induction motors, however, there are certain fields where 25 cycles will show better results. This is in very slow speed work, or very slow speed in proportion to the capacity. It is a rule in practically all types of generators and motors that the greater the number of poles, the greater must be the total magnetizing ampere turns. In windings excited by direct current, the number of exciting turns may be increased with increase in the number of poles, at a certain expense in copper, so that the actual exciting or magnetizing current may not be excessive, even with a very large number of poles—that is, in very slow speed machines. But in induction motors, the same turns are used for magnetizing and for generating counter e. m. f. The latter condition usually so fixes the number of turns, in a given capacity and speed of machine, that the actual magnetizing current increases very greatly with increase in the number of poles,—that is, with decrease in speed, so that, with a large number of poles, this magnetizing current becomes so large in comparison with the work current that the characteristics of the machine are very seriously affected. This increase can be limited to a certain extent by increasing the dimensions of the machine,—that is, its cost. Herein is where 25 cycles may give considerable advantage over 60 cycles. For instance, a 4-pole, 25 cycle motor will have about the same speed as a 10-pole, 60 cycle motor. The 4-pole motor should, and usually does have smaller magnetizing current than the 10-pole. However, the 4-pole machine for the same speed should require more material than the 10-pole, on account of higher magnetic flux conditions. Therefore, if the 10-pole machine were made of larger dimensions than the 4-pole, but utilizing the 4-pole magnetic material, its magnetizing current might be made fairly comparable with that of the

4-pole machine. However, with the same total useful material, but arranged in larger dimensions, the idle material, such as frame, supports, etc., will be somewhat greater in the 10-pole machine of the same speed, and therefore, in general, for equal speed and equal characteristics, the 60 cycle induction motor should cost more than the 25 cycle. However, for general power distribution with relatively small motor capcities, it is not correct to compare a 10-pole 60 cycle motor with a 4-pole, 25 cycle; for, in most cases, 60 cycle motors of higher speed can be used, such as eight, six and four-pole, giving respectivley 900, 1200 and 1800 r.p.m., neglecting the small slip. These higher speed and smaller number of poles in general more than offset the advantages of the 25 cycle, 4-pole, 750 r.p m. motor as regards cost and characteristics, and at the same time, the greater choice in speeds is very advantageous. In 25 cycles, the highest speed is 1500 r.p m., with two poles, and experience has shown that, in size and construction, a 2-pole induction motor has very little advantage over a 4-pole, except possibly in very small capacities. Therefore, 60 cycles, with its 4-pole 1800 r.p m., 6-pole 1200 r.p.m., 8-pole 900 r.p.m. motors, has a decided commercial advantage over the 25 cycle system with its 2-pole 1500 r.p.m., and 4-pole 750 r.p.m. motors.

However, when we compare, for instance, a moderate capacity 12-pole, 250 r.p.m., 25 cycle with a 30-pole, 240 r.p.m., 60 cycle motor we may find the advantage considerably in favor of the 25 cycle,—so much so that if all the motors to be used in a given plant were of this speed or lower, and there were no other offsetting advantages for 60 cycles, such as lighting, etc., then the proposition would look like a good one for 25 cycles. However, if only a small percentage of the total load is represented by such low speed motors, then the 60 cycle supply may make otherwise a sufficiently good showing to warrant its use. If, however, we go to the extreme case of moderate, or even very large, capacity motors at 75 to 100 r.p.m., then we run into almost prohibitive constructions with 60 cycles, either in size or in operating characteristics. At 60 cycles, such motors are liable to have such low power factors that the actual current taken by the motors is so large compared with the work current that, even with poor performance, a very large motor is required for a given capacity. In 25 cycles however, such motors can make a very much better showing. Therefore, at the present time, 25 cycles prepresents the most suitable frequency

for such motors. However, hope may be extended for the 60 cycle motor. If such motors are to be operated at constant speed, or even under variable or adjustable speeds, as has been described under an earlier subject, it is possible and practicable to overcome the difficulty of the poor power factor and large current from the supply system by connecting a special low frequency exciter in the secondary circuit of the induction motor, which will supply the magnetizing current to the secondary instead of the primary, just as in the non-synchronous type of condenser already referred to. This does not eliminate the magnetizing current in the motor, but simply puts it in the secondary circuit.

The above is a considerable digression from the central station problem, but it has a direct bearing on the purchase of power by fmills from central stations. From the above, it is obvious that or the general sale of motor power to varied industries, the 160 cycle central station has a direct advantage over the 25 cyce, in the great majority of service.

When it comes to the question of delivering direct current from an alternating-current system, the 25 cycle system, in connection with rotary converters, is generally assumed to have considerable advantage over the 60 cycles. However, even that advantage is disappearing, due to recent advances in the design of high speed apparatus for converting from alternating to direct current. Where motor generators are used, 60 cycles in general allow a more satisfactory choice of converting set; for, in many cases, for a given capacity, the 60 cycle set can be given a somewhat higher speed than the 25 cycle. Therefore, the advantage of 25 cycle, if such exists, must lie in rotary converters. But recent advances in 60 cycle rotary converter construction have made the 60 cycle rotary a strong, and pretty reliable competitor of the 25 cycle rotary,—so much so that, at the present time, quite a number of electric railways have shut down their own D. C. generating stations, and are buying power from 60 cycle central stations through 60 cycle rotaries. This development has removed one of the most serious handicaps of the 60 cycle system, so that the present tendency of central station work, and even power transmission, is strongly toward 60 cycles. The steel mill engineers should therefore keep this tendency strongly in mind.

SOME CONTROLLING CONDITIONS IN THE DESIGN AND OPERATION OF ROTARY CONVERTERS

FOREWORD—This paper was presented at the twenty-eighth annual convention of the Association of Edison Illuminating Companies at Hot Springs, Va., September, 1912. At that time, the synchronous booster type of converter was becoming well established and it was the author's purpose to show in this paper some of the conditions of commutation which were encountered in the synchronous type of machine.—(ED.)

EXPERIENCE shows that the rotary converter is one of the most satisfactory and reliable of the various types of rotating electrical machinery. In its efficiency of transformation, its commutation and temperature characteristics, and its operating characteristics in general, it makes an extremely good showing. Furthermore, it is a type of machine which has not changed greatly in the last decade. The more recent developments have been principally in the use of commutating poles and in a very material increase in the rotative speeds, these two features, however, being closely allied, as will be shown later.

In considering the various characteristics of the rotary converter, such as its current and voltage capacities, e. m. f. regulation, commutation and the use of commutating poles, maximum speeds permissible with a given output, etc., certain fundamental conditions or limitations in the design, are of controlling importance. In order to obtain a fuller understanding of the possibilities and capabilities of such apparatus, a brief consideration of these fundamental conditions will be given.

COMMUTATION LIMITS AND SHORT-CIRCUIT E. M. F.'S

One condition of controlling importance in all commutating machinery is the commutation. If the machine does not commutate well, then perfections in other features are overshadowed. High efficiency, low temperature rise, and low first cost, do not outweigh bad operation at the commutator.

In the ordinary commutating machine, the armature winding, when carrying current, sets up local magnetic fields, or fluxes, across which the armature conductors cut and thus generate

e. m. f.'s, just as when they cut across the main field fluxes. These local fields, due to the armature ampere turns, usually have peak values at those points on the armature where one or more armature coils are short-circuited by the brushes on the commutator. The conductors or turns which are thus short-circuited, have certain voltages generated in them, and the brushes are short-circuiting across these voltages. It may thus be said that there is a certain short-circuit voltage per armature coil, or between adjacent commutator bars, which may be called *the inherent short-circuit e. m. f. per bar*. If the brush is wide enough to cover several bars, then it short-circuits the voltages of several bars. The average value of this may be called *the inherent brush short-circuit e. m. f.* The value of this latter is of utmost importance in commutating machinery, for it is upon this, and the resistance of the brush, that the amount of short-circuit, or "local," current depends.

When the *work* current, or that which flows to the external circuit, passes from the commutator to the brush, it should be distributed evenly over the whole brush contact, providing there are no disturbing conditions. On the basis of uniform distribution of current over the brush contact, the minimum current density at the brush contact would naturally be obtained, which would be an ideal condition in many ways. This ideal distribution of the work current over the brush contact area will be called the *apparent current density in the brush*, to distinguish it from the *true current density*, which is due to the resultant current in the brush, which is always greater than the work current.

The principal cause of the difference between the true and the apparent densities in the brush lies in the local or short-circuited current, due to the brush short-circuit voltage just described This local current distributes over the brush contact according to the short-circuited voltages under the brush contact, and is thus practically zero at the middle of the brush, and maximum at the edges, flowing from the commutator to the brush at one side of the mid-point, and from the brush to the commutator at the other side. It thus adds to the work current at one side of the brush, and subtracts from it at the other side, and, not infrequently, the local current is so great, relatively, that the resultant current at one brush side will be several times that due to the work current, while at the other edge it will actually be in the opposite direction.

This condition can be illustrated by Figs. 1, 2 and 3.

Fig. 1 represents the conditions where only the work current flows.

The height *ab*, which is uniform, represents the value of the work current.

Fig. 2 represents the conditions under the brush if only the local current is considered (on the assumption that the field due to the armature work current is present, but the work current itself is absent).

ac represents the maximum current in one direction at one edge of the brush, while *de* represents an equal and opposite current at the other edge.

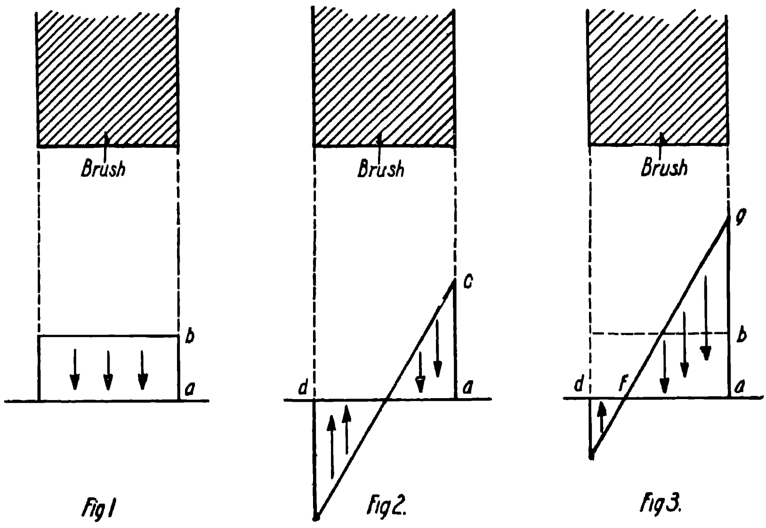


Fig 1 Fig 2. Fig 3.

Fig. 3 represents the conditions when both currents are present. At one edge of the brush the current is excessive compared to the work current, while at the other edge the current is in the opposite direction. Obviously, the part of the brush between *d* and *f* in this figure is not only useless, but is worse than useless, for it not only does not carry any current into the armature, but actually adds to the current carried by the part between *a* and *f*. Therefore, if the part between *d* and *f* were actually cut away, the remaining part between *a* and *f* would not be worked as hard as before. This diagram represents a somewhat extreme condition, but is not an unusual one, as experience has shown, for in a great many commutating machines in actual service, improved results have been obtained by narrowing the brush contact a certain

amount. Obviously, the apparent current density in the brush would be represented by the height *ab*, while the true current density would be represented by the maximum height *ag*, in Fig. 3, which may be several times as great as the height *ab*.

It is evident from consideration of the above figures that the conditions would be greatly improved by any reduction in the value of the local or short-circuit current. Narrowing the brush, as mentioned above, is, to a certain extent, effective. This reduces the local current, but at the same time it reduces the effective path for the work current. Another partial remedy would be in the use of higher resistance at the brush contact, such as is furnished by certain makes of brush. This would reduce the local current without reducing the area of the brush contact, but at the same time it introduces resistance in the path of the work current, which is practically equivalent to reducing the area of the path. It is, therefore, to a certain extent, equivalent to narrowing the brush. A third and more satisfactory method is to reduce the inherent short-circuit voltage across the brush, while at the same time retaining the full width of the brush. This, however, is a question of design and the proportioning of the machine itself, and obviously such modification cannot readily be supplied to a machine already constructed. This method of correcting trouble will be referred to again.

The above figures illustrating the effect of the local current, do not make the story quite as bad as it actually is. If the brush contact resistance in a given brush were of constant value, irrespective of the current in it, then the above illustrated conditions would hold. But the brush resistance is actually variable in effect; that is, at ordinary working current densities, the e. m. f. drop across the brush contact does not increase directly with the current, but at a much less rate. This, therefore, is equivalent to a decrease in the resistance of the brush contact with increase in current and, unfortunately, this decrease is very pronounced, even within the limits of permissible current densities. Therefore, with local current in the brush, giving high densities at the outer edges, the resistance of the brush may be so reduced as to give even worse distribution than indicated by Fig. 3.

Considering next, actual permissible brush drops, it may be noted that, as the local current enters at one side of the brush and leaves at the other side, the contact resistance in series with the

local current path is twice the ordinary contact resistance between brush and commutator. From an examination of a large amount of data on brush drops, it appears that, with the ordinary commercial brushes, there is about 1 to 1.25 volts drop between the brush and the commutator when carrying currents of 30 to 50 amperes per square inch. With the brush contact resistance indicated by these drops, it is evident that with a short-circuit voltage of 2 to 2½ volts across the brush, a local current could flow which would have a value at the brush edges corresponding to a current density of 30 to 50 amperes. Assuming a short-circuit voltage which would give a density of 50 amperes per square inch at the edges, then with a work current flowing which also gives an apparent current density of 50 amperes, the resultant density at one brush edge would become zero, while at the other edge it would become 100 amperes per square inch. With brushes having a low contact resistance the conditions would be worse, and there would be a current of negative direction at one edge of the brush.

In practice, an inherent brush short-circuit e. m. f. of 2 to 2½ volts is very seldom found, as it is too low a value for commercial designs. However, with much higher short-circuit e. m. f.'s the conditions would obviously be very much worse than indicated above, and yet in commutating machines of the non-commutating pole type, inherent short-circuit e. m. f.'s of 4 or 5 volts would be considered relatively low, and even 7 or 8 volts would not be considered unduly high in some cases. Evidently, with such e. m. f.'s actually across the brush, the local currents in the brush should be excessive and there should be severe sparking and burning at the brushes and commutator. However, this impossible condition is overcome to a considerable extent by generating an opposing voltage in the short-circuited coils. This result is obtained in non-commutating pole machines by shifting the brushes toward one of the pole corners to such an extent that the short-circuited coils are cutting across a small part of the main field flux, which thus generates a small e. m. f. in them. The shift of the brushes must always be in such a direction that this e. m. f., due to the main field, is in opposition to the short-circuit e. m. f.

To illustrate the above case, let it be assumed that the inherent short-circuit voltage across the brush at full load, with no lead at the brushes, is six volts. This, if not partially neutralized, would generate an unduly high local current, so that the operating

conditions would be comparatively bad. Then, assume that the brushes are shifted so that the short-circuited coils are cutting across a main field flux sufficient to give three volts. As this is in opposition to the normal short-circuit e. m. f., the resultant short-circuit e. m. f. will be equal to 6 — 3 = 3 volts, which would not be anything like as bad as before. If, now, the load is removed from the machine, the brushes still retaining their lead, the three volts due to the main field will still be generated in the short-circuit armature coils, and there will be a no-load short-circuit e. m. f. of three volts, which would set up a local short-circuit current. However, as no work current is present under this condition, the short-circuit current could obviously be practically as great as the maximum value of the resultant current at the full load conditions. Therefore, if three volts short-circuit e. m. f. is permissible at full load, then four or five volts would be permissible at no load with practically the same commutating conditions as at full load. Therefore, the brush could be shifted forward into a field representing four volts, for instance, and thus at no load the short-circuit voltage will be four volts, while at full load it would be 6 — 4 = 2 volts. Therefore, by this means an impossible commutating condition, represented by no lead at the brushes, becomes a possible and practicable condition by giving a certain amount of lead. On non-commutating pole machines where a slight amount of lead is almost always required, a resultant short-circuit e. m. f. of three volts across the brush may be permissible, in some cases, at full load, but this cannot be assumed to be true in all cases, for there are other conditions, besides commutation, which are dependent upon the amount and distribution of currents in the brush. Of these other effects, the principal ones may be classified as, burning of the commutator and brush faces, high mica, and picking up of copper.

"WEAR" OR "EATING AWAY" OF COMMUTATOR AND BRUSHES

An elaborate and long extended series of tests has shown that when a relatively large current passes from a brush to a commutator or collector ring, or vice-versa, there is a tendency for undue "wear," as it might be called, of either the commutator or brush face, depending upon the direction of current. If the current is from the commutator to the brush, then the commutator face "wears" or is "eaten" away, while with the current from the brush to the commutator, the brush shows increased wear. This

is not a true mechanical wearing away of the commutator or brush, but is more like an electrolytic action, except that usually the particles taken from one surface do not deposit on the other. This rate of wear, as shown by test, is a function of the current density, the area of surface through which the current passes, and the contact drop. It is not directly proportional to the contact drop, or the current, but increases in a much greater proportion than either, or possibly even more rapidly than the product of the two. However, this is difficult to determine definitely, for with the wear once started, the trouble tends to accentuate itself. In other words, this wear will increase the contact drop and in turn the increase in contact drop will exaggerate the wear, so that the action is cumulative. This wearing action is apparently very slight in amount at *true* brush densities of 50 to 60 amperes per square inch, with carbon brushes, and if the commutating characteristics are very good, even much greater *true* densities are practicable, possibly up to 100 amperes per square inch. If the *apparent* density could be brought up to the true density; that is, if no current but the work current were present, then this high current density in the brush might be utilized in well designed machines, but this implies the absence of all local currents, also, perfect division of the current between the various brushes and brush arms, as will be referred to later. These two conditions are rarely attained in practice, and it would probably be dangerous to attempt apparent densities of 100 amperes per square inch in the ordinary carbon brush; but with commutating pole machines, where an opposing e. m. f. is generated in the short-circuited armature coils, the condition of relatively small local currents can be obtained by very careful proportioning of the commutating pole field. This means therefore that higher current densities in the brushes are feasible in commutating pole machines in general than in the non-commutating pole type. This has a direct bearing on the synchronous converter problem, as will be shown later when considering high speeds and maximum outputs with a given number of poles. However, the condition of perfect division of current between the different brushes has not been obtained in any simple, practical manner, and therefore some margin in brush current density must be allowed, even in commutating pole machines.

HIGH MICA

When the maximum current density in a brush contact is comparatively high, due to local currents or other causes, the commutator and brush "wear" may be relatively rapid compared with the mechanical wear due to friction of the brushes on the commutator. Under this apparent wear the commutator copper will be slowly eaten away by the current, but the commutator mica will not be materially affected. The mica must wear down by the mechanical friction of the brushes, If the "eating away" of the copper exceeds the mechanical wear of the mica, then a condition is reached which tends to increase the defect. As soon as the copper face is burned even an infinitesimal amount below the mica, the brush face tends to "ride" on the mica and thus has a reduced contact on the copper surface, or even none at all. This condition increases the burning action and eventually results in the so-called "high mica" where there is an actual gap between the brush and the commutator face Such a condition, once started, does not tend to cure itself, except under certain special conditions of operation. This high mica is frequently charged to the use of "hard" mica, which tends to produce a similar condition.

In some cases, this trouble from high mica may not be due to either excessive local currents or hard mica, but may be due to a relatively high proportion of mica to copper surface. Where comparatively thin commutator bars are used on a machine, the thickness of mica between the bars is not reduced in proportion, so that the percentage of mica may be relatively high. In consequence of this high percentage, the mica itself does not wear as rapidly as where a less total amount is used, while the copper may eat away at the same rate. This may therefore tend toward high mica, even where the local currents are relatively small. This condition of high percentage of mica is found particularly in high voltage machines where the number of bars is necessarily great and the thickness of each bar correspondingly small. On the other hand, with low voltage machines, the percentage of mica is relatively less, but other conditions may enter which partly neutralize this advantage. With lower voltages, for a given capacity, the current is correspondingly greater and, with a given contact drop, the losses are correspondingly increased and the tendency to produce noise by the brushes is also greater. To overcome these objectionable features, a soft, low resistance brush is frequently used. This, however, increases the tendency for

local currents and thus increases the copper wear, while at the same time a softer brush has less grinding action on the mica. Therefore, the low-voltage machine may also tend toward high mica.

A common, and very effective, remedy for this tendency toward high mica is to "undercut" the mica so that, everywhere on the brush wearing surface, it lies slightly below the copper surface. This does not remove the initial cause of the trouble, namely, the tendency to eat away the copper surface. But it must be considered that this initial tendency is usually very slight, and that the major part of the wear is due to the lessening of the contact between the brushes and the copper, thus increasing the burning tendency. In consequence of undercutting the mica, the brush can always maintain good contact with the commutator face, and thus the actual burning may be so slow as to be practically negligible. The true gain from undercutting the mica thus lies in the maintenance of more intimate contact between the copper and the brush.

This eating away of the commutator face may occur in service and yet the commutator may polish beautifully. This is found in some cases where the burning action is pronounced, and yet the conditions of operation are such that the mica can be worn down mechanically as rapidly as the copper burns away. This is not infrequently the case with machines where there are heavy peak loads of relatively short duration, followed by very much longer periods of operation with but little load. Under such conditions the burning action during the peak loads, with a consequent tendency to high mica, is hidden by the grinding action of the brushes on the mica during the long periods of operation at light load, so that the mica is kept practically flush with the copper and the copper surface is polished. That real burning is present is often indicated, in such machines, by relatively rapid wear on the commutator in grooves when the brushes are not well staggered.

"PICKING UP COPPER"

Another condition which sometimes accompanies high current density in the brushes, is the so-called "picking up of copper." Apparently, under some conditions, particles of copper, eaten away from the commutator face, will collect on the brush face. This may result in glowing at the brush contact, eventual burning away or "honey-combing" of the brush surface and general trouble at the commutator. This difficulty is possibly largely cumulative in its action. A slight coating of copper, or copper

"spots," may form on a brush. This gives a more intimate, or lower resistance, contact with the commutator face. With many brushes in parallel, an undue percentage of the total current may then pass through this one point, or brush, or low resistance contact, and the current density at this point may even become so great that the burning will be excessive. The resistance of the carbon brush, in itself, does not help this condition, for, unfortunately for this case, carbon has a negative coefficient of resistance so that heating lowers its resistance and thus accentuates the unequal division of current. One remedy for this condition is a more uniform contact resistance between the brush and the commutator. Experience has shown that undercutting the mica will frequently overcome this difficulty of picking up copper, particularly so if the machine can be "nursed" until the commutator face acquires a glaze. In some cases, a different grade of brush will be an improvement, but it is generally difficult to predict the most suitable brush, unless the inherent commutating characteristics of the machine are well known. This picking up of copper appears to be, to a great extent, a function of the current density, and is apparently somewhat of an electrolytic action, the copper eating away from the commutator and depositing upon the brush. Whatever tends to materially reduce the tendency for the commutator face to eat away, also tends to reduce the picking-up effect.

The foregoing features, while apparently minor in nature, are all of fundamental importance in commutating machinery in general, and particularly so in the case of commutating-pole rotary converters, especially in those commutating-pole rotaries which have what might be called self-contained or "auto" regulation of voltage, such as those with synchronous boosters, or with regulating poles.

COMMUTATING POLES

In the direct-current generator of large capacity and high speed the commutating pole has proved to be a real necessity. In such machines, due to the reduced number of poles and high armature ampere turns per pole, and consequent large fields or fluxes set up by the armature, together with the high speed, the inherent short-circuit voltages across the brush have reached excessive values, such as 12 to 14 volts at normal load. Such e. m. f.'s, unless largely neutralized, would obviously set up exces-

sive short-circuit currents under the brush. As a resultant short-circuit voltage under the brush of about 2 volts or less at full load is desirable, it is obvious that some such device as the commutating pole, which introduces an opposing e. m. f. in the short-circuited armature coils, is practically a necessity; and, furthermore, this opposing e. m. f. must *vary practically in proportion to the load*, in order to keep within the permisssible short-circuit limits across the brush at all loads. Shifting the brushes forward into an active field to neutralize 12 volts, for instance, is obviously impracticable, for if a sufficient opposing e m.f., such as 10 volts, is thus introduced into the short-circuited coils at full load, then it is so large that it will give prohibitive currents at no load if the same brush lead is maintained. Therefore with such a machine of the non-commutating pole type, the brushes must be shifted with the load, which, in many cases, is not a practicable condition. Consequently, the commutating pole, with its neutralizing e. m. f. varying in proportion to the load, is a necessary device with such machines.

In the rotary converter, however, the conditions are not so severe. On account of the alternating and direct currents in the armature winding opposing each other, the resultant armature magnetizing effect is very small compared with that of a corresponding D. C. generator. Therefore the magnetic fields set up by the armature winding are relatively much smaller, and the inherent short-circuit e. m. f.'s are also lessened. Therefore, the speed, current, number of poles, etc., being equal, the rotary converter would naturally have a materially lower inherent brush short-circuit e. m. f. than the D. C. generator. In many cases this e. m. f. may be within the permissible limits of the 6 to 8 volts, when the brushes are to be given a fixed lead, while the corresponding D. C. generator might have 10 to 12 volts, which cannot be sufficiently corrected by a fixed lead. Therefore, the addition of the commutating pole to the rotary converter usually will not represent the same gain or improvement as in the D. C. generator, and its use, in some cases, is more in the nature of a refinement of operation than an absolute necessity. It may be suggested that, by the use of commutating poles, the inherent short-circuit e. m. f. might be made higher, or given the same values as in D. C. generators, with a consequent gain in cost of the machine, due to the use of higher speeds or a reduced amount of material. There might be some saving, with such a procedure, but, on the other

hand, there are certain operating conditions in commutating pole rotaries, not encountered in D. C. generators, which make it inadvisable, in many cases, to work at as high commutating limits as on commutating-pole D. C. machines. In D. C. generators the armature has a definite magnetizing action, depending upon the current carried, and this magnetizing action is always of the same value for the same armature current, regardless of speed, voltage, or any other condition. The function of the commutating-pole winding is to overcome or neutralize this armature magnetizing effect at the point where the armature coils are short-circuited, and in addition, to set up a magnetic field in the opposite direction to that which the armature winding will tend to establish. A positive relation is thus established which is practically unaffected by conditions of operation.

In the rotary converter, however, the conditions are somewhat different. As the resultant armature ampere turns are normally very small, the commutating-pole ampere turns required are correspondingly reduced, and have a much smaller value than on a corresponding D C machine. If the resultant armature ampere turns always held a definite value, for a given direct current delivered, under all conditions of operation, then the commutating-pole winding could readily be given the necessary proportions for setting up the desired commutating field. But the resultant armature ampere turns in the rotary can vary over a considerable range, while delivering a direct current of practically constant value, and consequently with a constant commutating-pole strength. Obviously, with a constant commutating-pole strength and a resultant armature magnetizing effect which can vary over a considerable range, the resultant short-circuit e. m. f. can also vary up or down, while commutating a given current, and, if the variation is excessive, bad commutating conditions will result. As the average value of the resultant ampere turns of the rotary converter armature is only about 15 percent of that of the same armature as a D. C. machine, it is obvious that a relatively small unbalancing of the opposing alternating and direct currents may give a great increase in the resultant ampere turns, which may greatly disturb the commutating-pole conditions and set up relatively large resultant brush short-circuit e. m. f.'s.

As such disturbances can actually occur in rotary converters from several causes, it is usually advisable to make the inherent short-circuit e. m. f as small as possible, without undue sacrifice in

the design of the machine. One condition which can produce the above unbalancing between the alternating and direct currents is "hunting." When a rotary hunts it alternately stores energy in the rotating parts and returns it to the system, during which the speed of the rotary oscillates with respect to the frequency of the supply system. While storing energy in the moving parts the alternating-current in-put is higher in value and, in restoring power to the line, is lower in value than is required for the average D. C. output. In consequence, where hunting occurs, the resultant armature ampere turns periodically vary in value and there is a corresponding periodic short-circuit voltage across the brush which may reach excessive values and cause vicious sparking, or even flashing.

Another cause of variation in armature reaction is found in sudden changes of load on a rotary converter. When a sudden load is thrown on, the rotary may momentarily carry part of its load as a D. C. generator. This means disturbance of the commutating field, in the wrong direction, at the very moment that this field should be at its best. But by avoiding too high normal short-circuit voltages in the armature winding, the above conditions of undue voltages across the brush can be relatively lessened.

In rotaries with "self-contained" regulation, another disturbance is introduced, which will be described later.

RELATION OF SPEED TO CURRENT CAPACITY, ETC.

In the design of all rotating machines for transformation purposes, as high speeds should be chosen as conditions of economical design will allow. In D. C. generators, the speeds and the number of poles have no rigid relation to each other. Thus, a 1000 kw, 500 r. p. m. generator could have from 4 to 12 poles, as desired. For 600 volts, and corresponding currents, it could have 6 poles, for instance. For half this voltage, with twice the current, it could have 12 poles, with the same speed. There is therefore a certain freedom in the design of such a machine.

In the rotary converter, however, the above condition is absent. The frequency is fixed, which at once fixes the relation of the number of poles to the revolutions per minute, for the frequency is the product of the two. Therefore, if a 600 volt, 1000 kw 25 cycle rotary converter would require 6 poles at 500 revolutions, then a machine with half this voltage and twice the current and with 12 poles, must operate at 250 revolutions, and not 500.

In rotaries where the current per brush arm, and per pole, is at the highest permissible limit, the number of poles must vary directly and the speed inversely, as the total current to be handled. Thus, for example a 270 volt rotary of large capacity will inherently have more poles, and will run at a lower speed, than a 600 volt rotary of equal capacity, which is not necessarily the case with D. C. generators.

The minimum number of poles in either a rotary converter or a D. C. generator is practically fixed by the direct current to be handled. There is a practical limit to the current per brush arm, as fixed by the permissible current density in the brushes and the permissible breadth of the commutator face. There are physical conditions which limit the breadth of the commutator face, depending upon the speed, expansion conditions under temperature, etc. The maximum breadth being determined for any given case, the circumferential thickness of the brushes being fixed by limits of inherent short-circuit e. m. f., and the current density in the brushes being fixed by limits of brush and commutator wear, as before described, it follows that the maximum current per brush arm is pretty definitely fixed, with present constructions. For a given total output in current, the limiting current per brush arm thus fixes the total number of brush arms and poles, and thus fixes the speed for a given frequency. These limiting conditions are pretty closely approached in recent 25 cycle rotaries of the commutating pole type.

LIMITING CURRENT PER BRUSH ARM

As indicated above, this is a function of the length of the commutator, which depends, to some extent, upon the peripheral speed of the commutator face. With 25 cycle rotaries, considerably lower peripheral speeds are obtainable than with 60 cycle rotaries, without unduly decreasing the distance between adjacent brush arms or neutral points The peripheral speed, in feet per minute, of any commutator is equal to the *distance in feet* between two adjacent neutral points, *multiplied by the frequency in alternations per minute*; thus, with 25 cycles per second (or 3000 alternations per minute) with one foot, or 12″, between adjacent neutral points, the commutator peripheral speed will be 3000 ft. per minute. With 60 cycles per second (7200 alternations per minute) with 8″, or 2-3 ft. between adjacent neutral points, the peripheral speed of the commutator will be two-thirds of 7200 =

4800 ft. per minute. Or, in other words, with equal peripheral speeds, the 25 cycle rotary can have 2.4 times as great distance between neutral points as a 60 cycle machine. The above relation of commutator speed to frequency holds true regardless of the number of poles. It therefore follows that, as the 25 cycle machine can have much lower peripheral speed at the commutator, the difficulties of building the commutators should be very much less. It should therefore be practicable to build much wider commutators for 25 cycle rotaries than for 60 cycle, and experience bears this out. With the wider commutators, at 25 cycles, the brush bearing surface is increased, and thus with a given width of brush, the number of brushes per arm can be correspondingly greater than for 60 cycles.

In the second place, even with considerably lower peripheral speeds at the commutator, the thickness of the commutator bars will be considerably greater, in most cases, than can be used on 60 cycle machines of the same rated voltage. In consequence, with a given thickness of brush, fewer bars will be short-circuited on the 25 cycle machine, than on the 60 cycle, and therefore, in general, somewhat thicker brushes are permissible for given inherent brush short-circuit limits. This, again, allows more current per brush, so that the 25 cycle machine has an advantage in total current per arm, due to the thickness of brushes, and to the number of brushes which can be used per arm. On the basis of a brush ¾″ thick, and a current density of 50 amperes per square inch, experience shows that a normal rated current of about 1000 amperes per brush arm is possible on large 25 cycle rotaries which are designed to carry heavy overloads for moderate periods, such as two hours. With such brush thickness, these rotaries can be designed for moderately low inherent short-circuit voltages and abnormal refinement in proportioning of the commutating pole dimensions is not required, as extremely close adjustment of the resultant short-circuit voltage is unnecessary. With thicker brushes, such as 1″ instead of ¾″, it is possible to operate at somewhat higher current per arm, possibly up to 1200 amperes, but this is at a certain expense in higher inherent short-circuit e. m. f.'s and less all-around margin in general. With the thicker brush there is necessarily a greater tendency for local currents, and therefore closer proportioning of the commutating poles is required. However, with equally careful proportioning, with the ¾″ thickness of brush, the results would be relatively better also.

One of the possible troubles with very heavy currents per brush arm, lies in the difficulty of obtaining equal division of current among all the various brushes per arm. The possibility of trouble is apparently considerably increased, the greater the current per arm, and if this greater current per brush arm is obtained by the use of thicker brushes rather than by greater length of commutator, then the result is practically equivalent to working the machine harder, or nearer the limit. If the operation of two commutators be compared, one with a ¾″ thickness of brush and the other with a 1″ brush, both having such brush capacity that they are worked at equal apparent current densities, then, other conditions being equal, the commutator with the ¾″ brush will be found in general to give superior results. And experience has shown that in many cases the 1″ brush can have its width cut down to ¾″ width, with apparent improvement in operation. However, if both the ¾″ and 1″ brush actually show the same *true current density;* that is, including all local currents and unbalancing of current between brushes, then with equally well proportioned commutating poles, there should be but little difference in the operation with the two thicknesses of brushes.

Assuming 1000 amperes as representing the limiting current per arm with ¾″ brushes on 25 cycle machines, then on 60 cycle rotaries, which usually have brushes of less than ¾″ thickness, and considerably narrower commutators on account of higher peripheral speeds, the maximum rated current per arm will be in the neighborhood of 600 amperes. This smaller current per arm should apparently handicap the 60 cycle machine compared with the 25 cycle, but, in compensation, on the basis of equal revolutions per minute, a 60 cycle rotary will have 2.4 times as many brush arms, which more than makes up for the lower current per arm. Therefore, from this standpoint it should be feasible to operate the 60 cycle rotary at considerably higher speed than the 25 cycle. This, however, has not been carried to the limit, in present practice, as the speeds which would be obtained would be so high, in some cases, that present commercial conditions will not allow them. This means, therefore, that we have probably not yet reached the possible maximum speeds which are practicable with 60 cycles.

E. M. F. REGULATION OF ROTARY CONVERTERS

There are three well-known methods for varying the D. C. e. m. f. of rotary converters, with a fixed A. C. supply voltage. These three are known as the induction regulator, the synchronous booster, and the regulating-pole methods of control. In the induction regulator method, an induction regulator varies the A C. voltage up or down over the range necessary to give the desired D. C. voltage change. In the synchronous booster method, an A. C. generator of a capacity corresponding to half the range of control is operated synchronously with the rotary converter and, by means of direct-current field control of this booster, the A. C. e. m. f. supplied to the rotary is varied up or down. In the third method each main pole of the rotary proper is made up of two or more smaller poles, one or more of which may have the excitation varied and by this means the ratio of the D. C. to the A. C. e. m. f., in the rotary converter armature itself, may be changed.

Each of these three methods has certain possibilities, advantages, and disadvantages, depending upon the conditions of operation The induction regulator method has been used very considerably in the past, but is but little advocated, in more recent work, due probably to the fact that it is more complicated and expensive than other methods Both the synchronous booster and the regulating pole methods of voltage regulation have been used more or less extensively, however, principally without commutating poles. With the introduction of the latter, a new problem enters, which has a very considerable bearing on the design of such apparatus, especially in machines of very large current capacity where the maximum permissible current per brush arm is approximated. This problem lies in the variable armature magnetizing force of the rotary, with change in D. C. e. m. f, while delivering a given current. Obviously, if the resultant armature ampere turns vary, the commutating-pole ampere turns should vary a corresponding amount. But if the commutating-pole winding is in series with the direct-current armature current, which may not be varied with change in voltage, the desired conditions are not met by such an arrangement. In this lies the real problem.

In the rotary converter with synchronous booster, but without commutating poles, the difficulty of variable armature reaction

such as indicated above, exists also, but is usually not serious, as indicated by the following:

In a rotary converter without synchronous booster or regulating poles, the ratio of the alternating current to the direct current is in normal operation pretty definitely fixed. The two currents oppose each other in the armature winding to such an extent that the resultant ampere turns vary between about 7 percent and 22 percent of the value in a D. C. machine, or with a mean of about 17 percent, when a full pitch armature winding is used. When a "fractional pitch" or "chorded" winding is used, this value is reduced, depending upon the amount of chording. This small resultant acts in the same direction as on a D. C. machine, and sets up a small field which affects the commutation slightly. Anything which will increase the ratio of the alternating-current in-put to the direct current will tend to reduce the resultant armature ampere turns, for normally the D C. effect is slightly in excess. Therefore, if the rotary should act, to a certain extent as a motor, thus receiving some A. C. in-put which is not transformed to direct current, the resultant armature ampere turns will be reduced, and may even pass the zero value and be in the opposite direction.

Again, if the rotary converter armature transforms some mechanical power received at its shaft, into direct current, so that the direct-current output is correspondingly greater than the A. C. input, then the resultant armature ampere turns will be increased.

In the synchronous booster method of regulation, the above is just what happens. The normal A. C. e. m. f. corresponds to the midway point on the D. C. e. m. f. range. When the booster neither "boosts" nor "bucks," the alternating current supplied corresponds properly to the direct current delivered, and the resultant armature ampere turns have a mean value of 17 percent approximately, assuming a full pitch winding. If the D. C. e. m. f. is boosted 15 percent, for example, the A. C. supply e. m. f. remaining constant, then obviously the current supplied to the alternating end is increased with respect to the current delivered by the D. C. end, in the ratio of the percentage boost. Therefore, the normal resultant armature ampere turns are reduced to $17 - 15 = 2$ percent.

Again, when the D. C. e. m. f. is reduced 15 percent, the direct current is increased 15 percent relatively to the A. C. and the resultant armature amperes are increased 15 percent, and

become 17 + 15 = 32 percent. Therefore, with a boost and buck of 15 percent voltage, while carrying the same direct-current load, the resultant armature reaction would be varied from 2 percent to 32 percent of that of a D. C. armature. This, however, is not serious in a rotary converter without commutating poles, as even with 32 percent armature reaction, the conditions are much better than in a D. C. machine where the armature reaction is 100 percent.

But when commutating poles are introduced the conditions are quite different. The commutating-pole winding normally should be equal to the effective or resultant armature ampere turns, plus the magnetizing ampere turns for setting up the required magnetic field under the commutating poles This latter component usually is small. Counting the effective armature ampere turns as 17 percent of that of a D. C. armature, and assuming the magnetizing component as 25 percent, then normally the total commutating pole turns would be 42 percent. If this 42 percent is furnished by series excitation from the D. C. end of the rotary, then it will be constant in value, with a constant value of the direct current, regardless of the variations in the D. C. e. m. f.

Now, suppose the D. C. voltage is boosted 15 percent by means of a synchronous booster, then the resultant armature ampere turns fall to 2 percent, as shown before, and, the commutating-pole ampere turns remaining at 42 percent, the difference, which is 40 percent, will all become magnetizing. Therefore, with a boost of 15 percent, the magnetizing component of the commutating-pole winding is increased from 25 percent to 40 percent, although the current to be commutated is unchanged. In the same way, if the D. C. voltage is bucked 15 percent, then the armature ampere turns become 32 percent and the magnetizing component of the commutating-pole field winding becomes 42 — 32 = 10 percent, when it should be 25 percent. Therefore, the commutating field strength actually varies up or down 60 percent from the required value, due to the synchronous booster action, when, in reality, it should remain constant.

If a resultant short-circuit e. m. f. of 3 volts across the brushes were allowed, then, this 60 percent variation in the commutating-pole strength, would mean that the inherent short-circuit e. m. f. is only 5 volts, which is normally neutralized by the commutating field. However, an inherent short-circuit e. m. f. of 5 volts is so low that it would require a rather difficult and expensive design, and therefore seven to 8 volts inherent short-circuit e. m. f. should

be considered in most cases. Obviously, with the above conditions of variable armature reaction, this would lead to vicious sparking conditions, especially at heavy overload, or at no-load conditions. Therefore, series excitation of the commutating pole by the direct current delivered, should not give satisfactory results. What is needed is a variation in the commutating pole excitation in accordance with any changes in the armature reaction of the rotary; that is, a reduced excitation at boost and increased excitation at buck.

Looking at the variable elements, it may be seen that the field current of the synchronous booster had its current in one direction at boost and the reverse direction at buck. Herein would appear to be a solution of the problem, by putting the booster field current through an *auxiliary winding on the commutating pole*, so that it opposes the series commutating-pole coil at boost and adds to it at buck. At first thought, this seems to fit the conditions perfectly, and, in fact, it does, at one definite direct current delivered, but does not do it perfectly at other loads. This is shown by the following figures. Assume the preceding value of 42 percent series ampere turns on the commutating-pole, with an additional auxiliary winding having the same percent ampere turns at full load as the percentage boost or buck. For example, with 15 percent boost, then at full load the auxiliary winding has 15 percent ampere turns, which are in opposition to the 42 percent series turns, while at 15 percent buck, at full load, the 15 percent auxiliary winding acts with the 42 percent series.

With 15 percent boost at full load, the armature reaction is lessened by 15 percent, and the total commutating field excitation is also reduced 15 percent by means of the auxiliary winding. Thus the resultant magnetizing component of the field winding remains at the required 25 percent. At no boost or buck, where there is no current in the booster field and auxiliary commutating-pole circuit, the resultant magnetizing component of the commutating-field winding remains at 25 percent, as explained before. When the booster field is reversed, in order to buck the A. C. voltage, the auxiliary field ampere turns on the commutating pole also are reversed, and at 15 percent buck they add 15 percent to the series commutating-pole winding, and thus give an effective magnetizing value of 25 percent instead of 10 percent, as given before. Hence, with this arrangement, the resultant commutating-field strength is correct for all the voltages, at the assumed full load current.

Considering, next, the half-load condition, then the armature ampere turns, both A. C. and D. C. are halved and the resultant armature reaction is also halved. However, for the same percentage boost or buck in D. C. voltage, the synchronous booster must operate *over the same voltage range as at full load*, and therefore, if the booster field current is the same for the same voltage range, regardless of load, then the auxiliary winding on the commutating pole adds or subtracts 15 percent, when, for correct commutating-field conditions, it should add or subtract only 7½ percent. Therefore, the excess field strength at the two extremes of voltage is 7½ percent, or 30 percent of the normal full load magnetizing component of the commutating-pole winding of 25 percent, which was assumed as that required to neutralize the assumed inherent brush short-circuit e. m. f. of 8 volts. A 30 percent component of this would mean 2 4 resultant volts across the brush. Practically the same condition would also be found at 50 percent overload. This apparently would not be a prohibitive condition if it represented the full range of operation. At no-load, however, the excess effect of the auxiliary winding would be 15 percent instead of 7½ percent, giving a magnetizing component equal to 60 percent of the normal magnetizing effect of the commutating-pole winding, or 4.8 resultant volts across the brush, which is higher than desirable. The above arrangement therefore fails for extreme changes in load, if the synchronous booster excitation is constant for a given percentage boost or buck, independent of the load on the rotary. What is required with this scheme is an excitation of the synchronous booster, which, for the same range of voltage variation, increases and decreases with the load on the rotary. If, for instance, the 15 percent boost or buck could be obtained at no-load on the rotary, with one-half the field excitation that would be required for full load, then the excess ampere turns in the auxiliary winding on the commutating pole would be only 7½ percent total, at no load, instead of the 15 percent indicated above, and the resultant short-circuit e. m. f. across the brush at no-load would be 2.4 volts, which is entirely practicable.

From the above analysis, the solution of this problem is indicated. It lies in giving the synchronous booster such characteristics that its field current varies greatly with change in the load on the machine. This can be done in various ways, but most readily by designing the synchronous booster with relatively high ampere turns on its armature compared with its field ampere

turns, which is the very construction needed for making the most efficient and least expensive booster. In such a booster, with very high armature reaction, the field current can be made to vary over a relatively wide range, with a given percentage boost or buck, with any considerable changes in the armature current. With this construction therefore, it is practicable to build a synchronous booster type of rotary converter with commutating poles which will automatically adjust its commutating-pole exciting conditions *to suit changes in both load and voltage*, and thus there is no occasion to revert to the induction regulator, or other outside means of control.

As a proof of the correctness of the above principles, may be cited the largest capacity synchronous booster, commutating-pole rotary converters yet built, namely those recently furnished to the

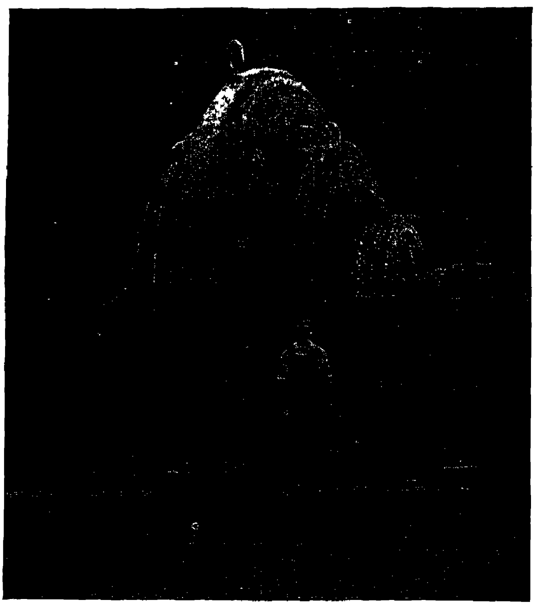


FIG 4. NEW YORK EDISON 3500 KW SYNCHRONOUS BOOSTER COMMUTATING POLE ROTARIES.

New York Edison Company, one of which is shown in Fig. 4. These machines have a normal continuous rating of 3500 kw at 270 volts, and 13,000 amperes D. C. They must also carry 50

percent higher current for two hours, or 19,000 amperes at 270 volts. In addition, by means of their synchronous boosters, they can vary the voltage from 270 up to 310 or down to 230, while still carrying the rated current. As these are the most remarkable machines of this type yet constructed, a more complete decription of them will be in order.

The contract included five machines of 3500 kw, of the horizontal shaft type, and two machines of 3000 kw of the vertical shaft type, these latter to fit existing foundation plans. Each 3500 kw machine has a normal rating of 270 volts D. C. at 13,000 amperes, and is arranged to boost and buck approximately 15 percent. The synchronous booster therefore has a normal capacity of about 525 kw. The A. C. end of the rotary is arranged for 6-phase double-delta connection, requiring about 165 volts normal. The alternating current handled by each of the six collector rings is enormous, being approximately 6300 amperes. As the rotary has 28 poles, the current from each collector ring is carried by 14 leads, through the armature windings of the booster, to the rotary converter armature, where it divides into 28 paths, or one per pole, in the usual manner. The normal alternating current per armature circuit in the booster thus becomes 450 amperes, and in the rotary it is 225 amperes. As the machine has 6 collector rings, with 14 leads per ring, there are 84 windings on the synchronous booster. Each winding, however. simply consists of a single group of coils. As the booster has 28 poles, the same as the rotary itself, it has therefore three groups of coils per pole, the same as an ordinary three-phase generator. The booster armature is therefore simply an ordinary type of three-phase generator, except that the various groups of coils in each phase of the armature are not connected in series, but are in reality connected in parallel at the collector rings and at the main armature winding. This arrangement of the booster armature between the collector rings and the rotary converter armature thus presents a relatively simple arrangement, and tends toward compactmess and symmetry in the complete armature unit, as shown in Fig. 5.

The brushes on the collector rings are of a metal-carbon type, arranged in box-holders somewhat like ordinary carbon brushes. The type of metal-carbon brushes used has a very low contact drop under normal operation, being approximately 1-10 that of ordinary carbon brushes. The total number of brushes per ring is 20, and each brush has a section of 2.15 square inches,

thus giving a normal current density of 147 amperes per square inch.

On the direct-current end there are 28 brush arms, giving a normal rated current per brush arm of 930 amperes, approximately, and, for the two hours overload, of 1400 amperes approximately. There are 15 brushes per arm, each of ¾″ x 1¾″ section, thus giving an apparent current density of 47½ amperes per square inch.

The armature winding of this rotary converter is thoroughly cross connected in order to equalize the circuits,—a point of very considerable importance in commutating pole machines. The field poles are also equipped with heavy, well distributed copper dampers in order to destroy any tendency to hunt, which is a very important condition in commutating-pole rotaries, as previously explained.

The air gap under each main field pole is one-half inch. The use of this large gap naturally lessens any tendency for magnetic noises. As the brushes are of a lubricating type, and as the brush holders have special devices for adjusting the brush tension very accurately, the machines run very quietly. The commutator mica is undercut about 1-32 inch.

As these rotaries are equipped with both synchronous boosters and commutating poles, very careful designing as regards commutation characteristics, had to be done. The variable armature reaction, for all the various conditions of load and boost and buck of the D. C. e. m. f , were carefully calculated, and the commutating field proportions for correcting these reactions were determined. In the analysis and example previously given, showing what conditions of inherent short-circuit e. m. f., etc., could be allowed, and still obtain permissible results, and armature reaction of 17 percent under normal conditions and a magnetizing component of commutating-pole strength of 25 percent were assumed, giving a total of 42 percent. It was shown that, with a suitable auxiliary winding on the commutating pole, satisfactory conditions could be obtained from no-load to 50 percent overload, with 15 per cent boost or buck, with an inherent brush short-circuit e. m. f. as high as 8 volts. But in these 3500 kw New York Edison machines, by very careful analysis of the conditions of commutation, the inherent short-circuit e. m. f. at full load was gotten down to 6.3 volts instead of 8, while the average armature reaction was made as low as 11½ percent, instead of 17 percent, both of which

conditions are very favorable, compared with the former assumed permissible limits The normal or series commutating field ampere turns are 39 percent, instead of 42 percent, so that the magnetizing component is 27½ percent, the other 11½ percent simply opposing the normal armature reaction. This large magnetizing component is obtained by the use of a ¾″ air gap under each commutating

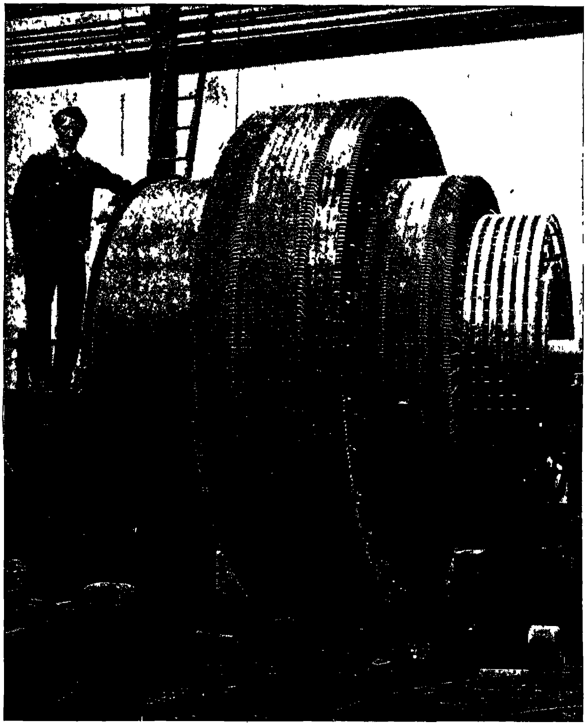


FIG. 5.

pole. Such a large gap, in itself, is of direct assistance in obtaining the desired distribution of the commutating field flux, and thus makes the design problem somewhat easier

A brief description of some of the unusual features of these machines may be of interest.

The rotary converter main frame or field is of cast steel, in order to reduce somewhat the overall dimensions, and keep inside the customer's requirements. The synchronous booster field frame is of cast iron. Both the main field and the booster have bolted-in laminated poles.

The commutator, main armature, booster armature, and collector rings are each assembled on separate spiders. The commutator spider, however, is pressed on the hub of the main armature spider, so that the shaft can be removed for shipment, without disturbing the connection of the armature winding to the commutator.

The commutator is of the through-bolt construction with heavy steel "V-rings." These rings are of large section in order to avoid distortion under the heavy clamping strains to which they are normally subjected. The commutator bars are designed to give the same deflection at all points. The commutator diameter is 120″, and the width of exposed face is 30″.

The two 3000 kw vertical units for the same company are of practically the same general design as the 3500 kw except that they are somewhat smaller, and operate at higher speed. They have 22 poles, and the normal current per brush arm is 1010 amperes, compared with 930 on the 3500 kw.

An extensive series of tests were made on both the 3500 kw and the 3000 kw, some of the results of which are as follows:

Armature iron loss at 270 volts, 3500 kw, 16.3 kw.
3000 kw, 13.8 kw.

That is, the normal armature iron loss in both sets is less than 0.47 of one percent,—a remarkably low figure.

The booster armature of the 3500 kw unit showed an iron loss at 15 percent boost or buck, of 4.6 kw, or less than 0.9 of 1 percent of its own rating, which is only 15 percent of that of the unit.

At 310 volts D. C , the 3500 kw unit showed 20.1 kw iron loss, and at 230 volts, 8 8 kw. The total iron losses, including the booster armature, thus varies between 13 4 kw and 24.7 kw over the entire range of voltage operation, or between 0.4 and 0.7 of 1 percent of the rated capacity of the machine.

Under all conditions the efficiency of the unit showed appreciably higher than the guarantees, due partly to the relatively low iron loss, as given above.

The following temperature test results were obtained on the 3500 kw unit:

Amp.	V.	Hrs. Run	Arm.Rise	Comm Rise
13000	270	10	31.5°C.	37°C.
12950	231	5	21.5	29.5
12950	317	6	31.5	30

On account of lack of certain facilities, a 50 percent overload temperature test was not made on this unit, but this was carried out on the 3000 kw unit, as shown in the following results of tests:

Amp.	V.	Hrs. Run.	Arm. Rise	Comm.Rise
*11100	270	13	17 5°C.	28.5°C.
*16650	270	2	42	45.4
11100	232	8	16 5	36
11000	312 5	8	27.5	30 5

In these temperature tests, the first run was made, in each case, for a period long enough to reach constant temperature. The other tests followed, while the machines were hot, so that steady temperature conditions were reached in a shorter time.

In the commutation tests, the results were equally satisfactory. At 270 volts the 3500 kw machine was tested from no-load up to 19,300 amperes; also, at 310 volts from no-load up to 14,000 amperes; and at 230 volts from no-load to full load; and at 257 volts, up to 15,550 amperes. Under all these conditions the commutation was remarkably good, and this may therefore be taken as evidence of the correctness of the principles given in the earlier part of this paper. Furthermore, as an illustration of the accuracy that is possible in the design of such apparatus, when the fundamental principles are sufficiently well known, it may be stated that, in the case of this 3500 kw unit, all drawings were made up, and all the above shop tests made on the completed machine, without any changes whatever, in the electrical or magnetic design, from the original engineering design specification. Also, on shop test, absolutely no re-adjustments were necessary in any of those parts where provision is usually made for such adjustment by reason of possible slight variations in material or workmanship, or inability of the designer to predetermine certain characteristics with sufficient accuracy.

---

*These runs were duplicated. The results given are the highest rises obtained from either test.

SIXTY-CYCLE ROTARY CONVERTERS

FOREWORD—This paper was prepared for the twenty-ninth annual convention of the Association of Edison Illuminating Companies at Cooperstown, N. Y., September, 1913. At the time it was presented, the subject of 60 cycle rotaries was becoming a very "live" one, as improvements in this type of machine were bringing it very rapidly to the front as a competitor of the 25 cycle rotaries.—(Ed.)

ONE of the most significant developments in the past year has been the greatly increased purchase of large 60 cycle rotaries by central station plants. Here is an example of a type of machine which has been more or less discredited in the past, but which, all at once, is coming prominently to the fore. The present machine itself is not radically different from its older forms, but it contains many minor improvements which, individually, do not stand out prominently, yet, collectively have served to overcome those little difficulties which formerly were just sufficient to put the machine in the questionable class. However, a number of general conditions were also involved in this improvement. It is the purpose of this paper to show wherein the new machine is superior to the older type, and also to indicate wherein a number of modifications, each in themselves of a small amount, have combined to form a relatively large improvement.

Shortly after the 25 cycle rotary began to be prominent in electrical work, that is, about 15 to 18 years ago, the problem of 60 cycle rotaries was also presented, as the relatively numerous 60 cycle plants also had need of economical means for transforming to direct current. In consequence, there being a field for 60 cycle rotaries, such machines were built and installed in a number of places. These early machines were in some cases, fairly successful, while, in others, they were failures. Apparently, in some of these cases of failure, the rotary itself was not entirely to blame, as it was operated under conditions which would now be considered impracticable, with our present knowledge and experience.

These early 60 cycle rotaries were very greatly handicapped in design by the limitations of commercial and manufacturing practice of those days. Relatively low speeds were considered necessary from the commercial standpoint, and with 60 cycles

this meant a large number of poles, even for relatively small outputs. Also, manufacturing limitations called for relatively low peripheral speed of the commutators. In those days commutator speeds of much in excess of 4,000 feet per minute were considered excessive, and unduly dangerous, both from the manufacturing and operating standpoints. Herein was a handicap of the worst sort upon the design. The peripheral speed of the commutator is equal to the distance between adjacent neutral points multiplied by the number of alternations per minute (revolutions per minute x No. of poles). On this basis, 3600 feet peripheral speed with 60

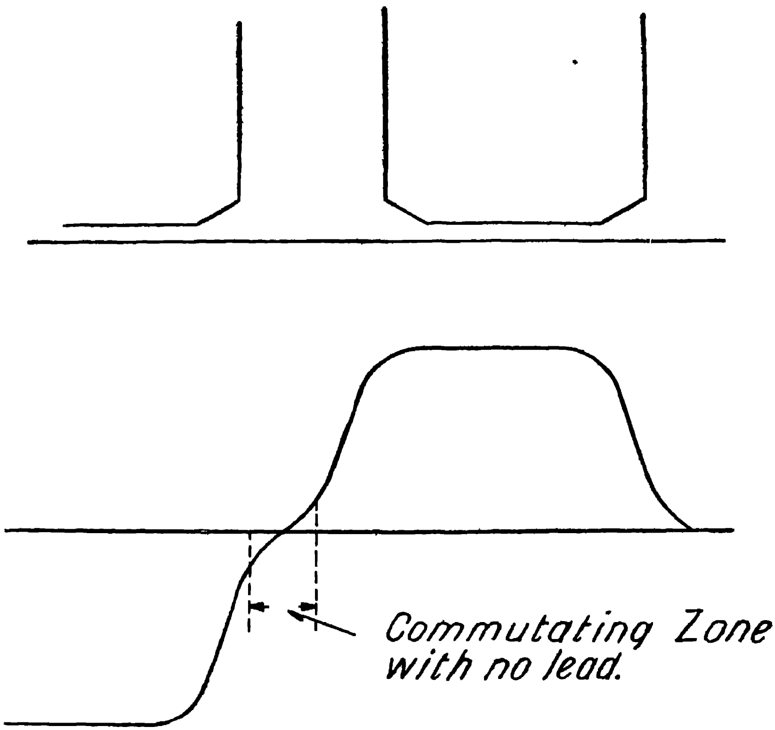


Fig. 1. Commutating Zone with No Lead.

cycles per second (7200 alternations per minute), gave 6 inches, between adjacent neutral points. Even 4200 feet peripheral speed gave only 7 inches between neutral points. It is obvious therefore that, even with this higher peripheral speed of the commutator, there was undue crowding of the brush holders,

which in itself was a bad feature. But the worst feature was in the fact that, with only 7 inches between commutator neutral points, the maximum permissible number of commutator bars was unduly limited. Assuming, for example, a thickness of bar-plus-mica of 3-16 inches, which is very thin, the 7 inches between neutral points would allow about 36 commutator bars between neutral points, or per pole. This number was ample for 250 to 300 volt machines, but for 600 volts, experience indicated that it was on the ragged edge, especially with the field flux distributions obtained with those early machines. In consequence, 60 cycle rotaries for 250 to 300 volts, rendered a better account of themselves than the 600 volt machines, and the latter were very much inclined to flash at times, due to the small number of commutator bars, and a high maximum voltage between bars.

The field flux distribution had something to do with the questionable operating conditions. With these earlier machines, very high peripheral speeds of the armature core were considered objectionable, for several reasons. One was, that the constructions of that time did not allow very high peripheral speeds of the armature windings, and, a second reason was that, with the relatively low speeds, and consequent large number of poles, the armature dimensions and cost would have been excessive for a given output. In general, a 12 inch pole pitch was considered as large as desirable or practicable, which corresponds to 7200 feet per minute at 60 cycles per second.

With this small pole pitch, in order to obtain a sufficiently wide commutating zone between the poles, it was necessary to make the poles relatively narrow. The use of narrow poles led into one difficulty, as regards flashing, as will be explained later, while widening the pole and narrowing the interpolar space led into another difficulty of flashing which was equally serious. The situation can be illustrated by Figs. 1 and 2. In Fig. 1 the field flux distribution is indicated for an extreme case of a pole face as wide as 8 in. and with only 4 in. interpolar space, the total pole pitch being 12 in., and the poles without polar horns. The "field form," which indicates the flux distribution, in this case has a relatively wide top, and the proportions are such that the maximum e. m. f. between the bars is about 40 percent greater than the average e. m. f. per bar. With 36 commutator bars, for instance, at 600 volts, the average volts per bar would be 16 2-3, and the maximum voltage per bar almost 24, which, in itself, may be a safe figure if

never exceeded. However, the flux distribution in the interpolar space, as indicated by Fig. 1, is such that there is almost no width to the neutral or commutating zone, and therefore the brushes are short-circuiting the armature coils in an active field, even at no load, and, in some cases, this short-circuiting action may be so great that there are excessive local currents in the brushes. Furthermore, with the neutral point so narrow, a very slight forward shifting of the brushes, to take care of load conditions, would place the brush in such a strong field at no-load, that there is danger of

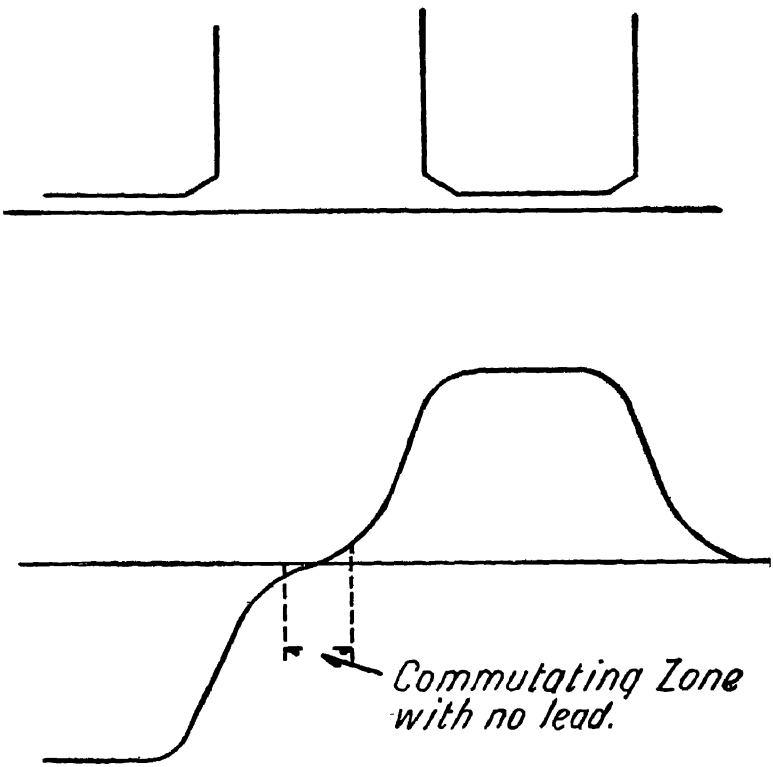


Fig. 2. Commutating Zone with No Lead.

flashing when the load goes off, or changes suddenly. Therefore, with such proportions, the neutral point would be too narrow for reasonably safe operation. The remedy for this particular condition, with these former machines, was obviously in the use of wider interpolar spaces, and consequently narrower poles, the pole pitch being limited to about 12 inches as previously stated.

In Fig. 2 is illustrated the conditions with the wider interpolar space, and narrower pole face, these being taken as 5½ in. and 6½ in. respectively, instead of 4 in. and 8 in. Obviously the flux conditions in the interpolar space are much better than in Fig. 1, and it should be possible to shift the brushes slightly for full load conditions without excessively bad conditions as regards sparking and flashing at no load. But the same figure also shows that the field flux distribution as a whole is considerably narrower at the peak value than in Fig. 1, and therefore the ratio of the maximum value of the e. m. f. per commutator bar to the average e. m. f. is much greater. In this case, the maxium per bar is about 65 percent greater than-the average, and, with 16 2-3 average per bar, the maximum becomes almost 28 volts, which is in the danger zone as regards arcing between bars, except in relatively small machines. Therefore, in overcoming the sparking and flashing difficulties incident to the narrow neutral zone of Fig. 1, an equivalent difficulty is encountered, due to the narrow field distribution, or field form. Plainly, in these older machines, whichever way we turned, we were in difficulty.

An obvious remedy for the above difficulties was in the use of wider pole pitches, which would allow both the commutating or neutral zone of Fig. 2, and the wider field form of Fig. 1. But increasing the pole pitch, with a given number of poles and given speed, means increasing the diameter of the armature, and even though the armature could thereby be narrowed, the cost of the larger diameter machine would necessarily be somewhat increased. The remedy for this condition was in reduction in the *number of poles* as the pitch was increased, thus keeping down the size of the armature for a given output. But reduction in the number of poles necessarily means higher speeds, which were formerly considered commercially objectionable, as no one had yet been educated up to high speeds. Therefore, between commercial limitations, difficulties in design and manufacturing conditions, the 60 cycle rotary was in a bad way. Mild attempts were made from time to time to increase the speed by decreasing the number of poles, but this could only be done commercially in relatively small steps. In such increases in speed, and decrease in the number of poles, other difficulties began to be encountered, such as somewhat poorer *inherent* commutating characteristics, due to the higher speed and greater current per brush arm to be commutated. The higher the speed was made, and therefore the

more commercial the machine became as regards size and cost, the greater were the inherent difficulties in the design. However, with increased experience in commutator constructions, one great advance was made by increasing the commutator speeds of the 60 cycle rotaries. Instead of approximately 7 in. between points, the distance was increased to 8½ or 9 inches for 600 volts, giving 5100 to 5400 feet peripheral speeds at the commutator face. This allowed as many as 45 to 48 commutator bars per pole, which is well within the range of good direct-current 600 volt practice. This increase in the number of bars reduced the average and the maximum volts per bar. In this manner, one of the principal weaknesses of the former designs was eliminated Also, by improved mechanical design which allowed higher peripheral speed of the armature windings, the pole pitch could be increased to about 16 in., instead of 12, without an unduly large diameter of armature for a given output. This also allowed a much better field flux distribution, or field form, such as in Fig. 1, and better interpolar space of Fig. 2. In consequence, the maximum voltage per bar on the 60 cycle rotaries has been brought down well within accepted D. C. practice for 600 volt work. For lower voltage work, these limitations have never been so prominent, but the same steps in the development have proved advantageous in lower voltage rotaries also.

With increased speed and decreased number of poles, the current per brush arm on the larger 60 cycle rotaries has gradually increased until it is practically double what it was on former machines of same capacity This higher current per arm, with the increased number of commutator bars per pole, and the higher speeds, all tend toward making the commutation problem more difficult. But at this stage in the development, the commutating pole began to loom up as a possibility in rotary converters, and this has furnished the latest important step in the improvement of these machines. By the addition of commutating poles, still higher revolutions are permissible than formerly. While relatively high speed rotaries of large capacity can be made without commutating poles, yet the addition of such poles has rendered the design less difficult and has allowed still further increases in speed, which are very welcome in the way of improving the standing of the 60 cycle rotary. With these higher speeds, and greater outputs with a given diameter of machine, the losses have not increased anything like in proportion, so that the difficulties cf the

60 cycle rotaries have been gradually increasing until now they are treading on the heels of the 25 cycle. In fact, when the greater efficiency of the 60 cycle step-down transformers is taken into account, the difference between the efficiencies of 60 cycle and 25 cycle converting units in large capacities, is not enough to attract any particular attention. Thus the use of the commutating poles has been of advantage principally in allowing higher speeds, with consequent better characteristics in general.

The modifications above described cover electrical defects principally. However, there were a number of other minor conditions in these earlier machines which might be considered as mechanical defects, or mechanical and electrical combined. These were found principally in the brush holder and commutator constructions, and in the materials in the commutator. On the higher voltage machines, in which a large number of commutator bars per pole was necessary, the thickness of each bar was, and still is, very small, and thus the proportion of thickness oi mica between bars to the thickness of the bars themselves is a very considerable percent. On this account, it has been difficult to obtain, in many cases, a wear or abrasion of the mica equal to the so-called copper "wear," which, in reality, is more in the nature of slow burning than actual wear from friction. No matter how perfect the commutation may be in appearance, there is always a slight tendency to burn the face of the commutator by the current passing between the commutator and the brushes. This burning normally may be at an extremely slow rate, but if the mica does not wear down at the same rate, the result will be that, after a time, the mica lifts the brush surface away from contact with the copper, and thus an almost infinitestimal gap exists between the brush and the copper of the commutator. This gap then exaggerates the burning tendency, and the difficulty thus accentuates itself: The hardness and wearing quality of the mica must be such that it will always wear down as fast as the copper burns away, so that normal contact is maintained between the copper and the brush. Where the percentage of mica is high, and where the mica varies in hardness, as is liable to be the case in practice, it is difficult to avoid more or less tendency to high mica and consequent trouble. This trouble is also accentuated by high commutator peripheral speeds, as it is more difficult to maintain uniform contact between the brush face and the commutator. In consequence, in 60 cycle rotary converters in general, and in high

voltages in particular, experience has shown that it is advisable to undercut the mica slightly, in order to avoid any tendency toward high mica, and also in order to be able to use brushes which contain some lubricant such as graphite. It is obvious that where any considerable grinding action by the brushes is necessary, to keep down the mica, such lubrication is not practicable to the same extent as where no grinding action is necessary. In consequence, on later types of 60 cycle rotaries, the commutator mica is usually undercut, thus allowing good contact to be maintained, and thus reducing any resultant burning action to the minimum. The true causes of the difficulty with high mica were *not* thoroughly appreciated, in the older 60 cycle rotaries, and, in consequence, in many cases, brushes of a hard, grinding character were used, with consequent increased losses and other disadvantages.

Also, on some of the older machines, even with the much lower peripheral speeds than at present, the design and construction of commutators were not as nearly perfected as at present, and there was always more or less danger from unevenness, and other defects, which, while not showing in themselves any particularly harmful results, would very often show indirect harm by causing high mica, sparking, brush troubles, etc.

Furthermore, in many of the earlier machines, the brush holders were not as rigid or as well suited for operation on high speed commutators as in present practice. In some cases, the operating characteristics of the rotary were greatly modified by simply changing the angle of inclination of the brush to the commutator, or the direction of inclination, or the brush pressure, etc. Brush chattering was not uncommon, and if there is anything which will surely cause bad commutators and commutation, it is severe chattering at the brushes, as this prevents good contact between the face of the carbon and the commutator face.

On many of the earlier machines the brush holders were not arranged with due regard to harmful results from incipient arcs between bars, or in the neighborhood of the brush holders and brushes. On sudden changes in load, or partial short-circuits, or even in normal operation in those cases where the maximum voltage between bars is unduly high, the not uncommon "ring-fire" around the commutator, due to burning of the carbon or graphite deposited on the mica or between bars, may develop into small arcs, with consequent vaporization of copper, the resultant vapor being a good conductor. If the brush holder or other parts are in close

proximity to the point where such small arcs may form, the conducting vapor may bridge across from the commutator face to the adjacent parts, where there is any considerable difference of potential between them, and may develop real arcs or flashes which are of a destructive nature, possibly necessitating the shutdown of the machine until the commutator can be smoothed up. In many of the older machines, with their very small distances between brush holders, and their generally crowded conditions, and their voltages per bar, such arcs were much more liable to occur than in the modern machines.

In the development of the 60 cycle rotary converter, there were other conditions beside commutation, flashing, etc , which had to be taken into account. The rotary converter is a synchronous machine, and must follow rigidly in step with its source of e. m. f. supply, or there will be difficulties in the operation. The early rotaries, in many cases, were operated from generators driven by slow-speed reciprocating engines, which did not run at uniform rotative speed, there being pronounced periodic speed fluctuations during each revolution. In some cases this condition was so bad that the generators in the power house would not operate decently in parallel. As the engines and generators varied in speed periodically, obviously the frequency of the electric circuit varied to the same extent, and any synchronous apparatus operated on such system would also have to vary in speed to the same extent, if the conditions were such that the machine should follow the supply system, as is the case in rotary converters. If the rotary did not follow rigidly, it would periodically either "under-run" or "over-run." This action is called hunting, and it was very serious at some of the early plants. Not infrequently the generators at the power house would not hold a rigid relation to each other, and hunted badly.

There are causes of hunting, other than variations in speed of the prime mover on generating unit, but usually these have been of secondary importance, and will not be considered further. The action of hunting of the rotary, with variations in speed of the generator, may be explained briefly, as follows: The rotary generates an alternating e. m. f. wave similar to that of the generating or supply system, but in opposition, or as a counter e. m. f. If the generator momentarily runs faster, then its e. m. f. will be ahead of that of the rotary. A motor current flows, tending to raise the speed of the rotary to that of the generator. If the

generator now drops back in speed, its e. m. f. wave drops back, and the rotary tends to deliver current to the generating system, thus tending to slow the rotary converter speed down to that of the generator. The action in the rotary is therefore one which tends to speed it up or slow it down to follow the generator. This action of the rotary, acting alternately as a motor or as a generator, is what constitutes hunting. Usually this action of following the generator speed is not a serious one, as a relatively small current may produce the necessary accelerating or retarding action. The difficulty is that the rotary may over-run; that is, it may speed up too much or drop back too much, and thus have an increased motor or generator action. In other words, this accelerating or retarding action may exaggerate the swinging effect, just as in the case of a swinging pendulum, where a very slight force, if timed just right, may gradually increase the swing of the pendulum. In those cases in the early rotaries where hunting was most severe, the periodic speed changes in the generating system were usually timed just right to cause the rotary to over-run, and thus exaggerate the hunting action.

The direct result of this hunting was visible in bad operation at the commutator. In the normal rotary converter, when running properly in synchronism, there is practically no armature reaction in the armature winding, such as is found in direct-current machines, for the alternating current supplied to the armature winding is in opposition to, and practically neutralizes, the magnetizing effect due to the direct current delivered. Therefore, as far as reactions on the field are concerned, the rotary is quite different from a direct current machine, and, at full-load, the armature has very little more effect on the field than at no-load. However, when the rotary is hunting, the current due to the hunting action above described is not balanced by the direct current delivered, so that this current acts like that in a straight A.C. or D.C. machine, and sets up magnetic fluxes in the interpolar space, and under the edges of the poles, which are harmful in character. These fluxes create bad commutating conditions by reason of the armature coils under the brushes being short circuited in a periodically varying magnetic field, which is not the case when the rotary is not hunting. Therefore, as a rotary hunts, there is usually periodic sparking at the brushes, which is in time with the periodic "beat" which usually can be heard in a machine when it hunts. This sparking will get more and more severe as the rotary hunts more,

until it may become so bad that the machine flashes over. This hunting in some of the early machines was a very puzzling phenomenon, and it was not until its nature and cause were determined that an effective remedy was applied. The corrective now universally applied consists in the use of copper dampers, or "cage windings," in the field pole faces of the rotaries, It is not within the province of this paper to explain the action of these dampers, but it may simply be said that they exert, to a certain extent, a braking action on the over-running action of the rotary, and also they damp out the field distortions due to hunting, such distortions materially exaggerating the hunting action. The dampers thus reduce one source of accentuation of the hunting, and exert a braking action to overcome the effects of the others. Such dampers were used early on 60 cycle rotaries, but in comparatively crude forms. Moreover, the angular variations in speed with 60 cycle generating units, were usually greater, in degrees per electrical cycle, than in 25 cycle machines, due to the much larger number of poles, and this made the hunting tendencies of the rotaries much greater, and the damping problem correspondingly more difficult than in 25 cycle rotaries. In consequence, 60 cycle rotaries should have had more damping action than 25 cycle machines, while, on the contrary, they actually had much less. The 60 cycle rotary was therefore considered a much more delicate machine as regards hunting, than its 25 cycle brother, and yet the fault was really in the generating plant in many cases.

The advent of the later 60 cycle turbo generating plants have been a large item in the successful development of the later type of 60 cycle rotaries. The problem of angular variation in speed of the prime mover has disappeared, and therefore the dampers on modern 60 cycle rotaries have to take care of only those secondary causes of hunting, which were present in the old conditions, but were masked by the much greater cause in the generating conditions. Also, with the newer high speed rotaries, with their relatively wider poles, it is practicable to add many more damper bars per pole than in the older machines, and, in fact, with the later machines, the problem of hunting is rarely encountered. However, a new problem in connection with hunting has come up in connection with the advent of the commutating pole, both in 25 and 60 cycles. In the commutating-pole generator, the ampere turns in each commutating-pole coil is sufficient to not only neutralize the entire magnetizing force of the armature winding

per pole, but also to furnish an excess flux for commutating. In the commutating-pole rotary, there is normally but little resultant magnetizing effect in the armature winding, due to the A. C. and D. C. currents being normally in opposition, and therefore the commutating pole winding must only be strong enough to neutralize the very small resultant armature reaction, and give, in addition, a magnetic flux sufficient for commutation. In consequence, the ampere turns on the commutating-pole winding may be only 30 percent to 40 percent of the total armature ampere turns, considered as in an A. C. or D. C. machine, whereas, in a D. C. generator, the commutating-pole winding is usually at least 125 percent of the armature ampere turns. Therefore, the rotary converter with its 30 percent to 40 percent commutating-pole ampere turns, instead of 125 percent, cannot act as a *generator* or *motor* with good commutation, as its commutating-pole strength is then much less than required. As a generator or motor, the armature reaction may not only over-power the commutating-pole winding, but may set up a strong magnetic flux in the wrong direction The commutating conditions may thus become much worse than if the commutating pole were absent Therefore, the commutating-pole rotary converter, when acting as a generator or motor, is a much worse machine than if the commutating-pole itself were omitted. Herein lies a source of possible trouble with commutating-pole rotaries. In case there is hunting, the armature will act alternately as a generator and motor, and, under such conditions, the magnetizing force of the armature may be such that it will demagnetize the commutating pole, or even reverse the flux under it, so that the machine acts in the same way as if it were operating with the current reversed in the commutating-pole winding, which would obviously give very bad commutating-conditions. Therefore, when the commutating-pole rotary hunts, it represents a worse condition than when a non-commutating-pole machine hunts to an equal extent. In consequence, with commutating-pole machines, it is very important to suppress any hunting tendency, and this, in general, requires somewhat better damping conditions than in the non-commutating-pole machine. Therefore, although improved conditions of generation, etc., have eased up on the damper requirements, yet the necessities of the commutating poles have made the damper requirements more rigid. In some cases, this has led to a very curious situation. It is well known that the commutating pole, whether on a direct-current

machine or on a rotary, should not have any closed conducting circuit around it, as such closed circuit acts as a secondary or opposing circuit in case of sudden change of load, preventing the commutating-pole flux from rising or falling in step with changes in load. Therefore, from the standpoint of commutating-pole construction, there should be no closed circuit surrounding the commutating pole itself. However, from the standpoint of the best arrangement of the damper to prevent hunting, a complete cage winding, tying all the poles together, as shown in Fig. 3, is, in general, the most economical and effective. But such a closed

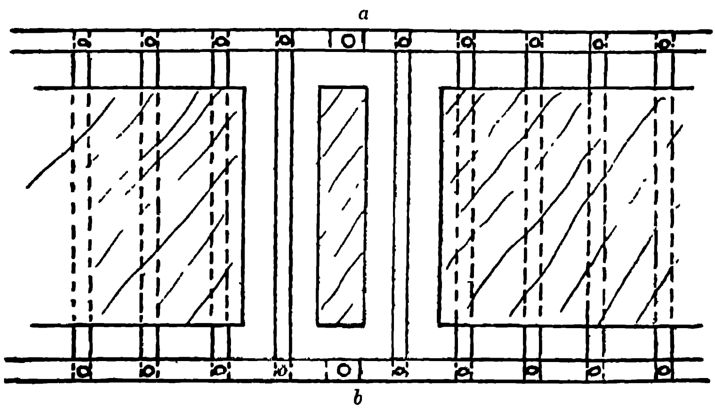


FIG. 3.

winding forms a rather effective closed secondary circuit around the commutating pole. One would therefore assume that it is inadvisable to close this damper circuit around the commutating pole, and that a break at *a* or *b* in Fig. 3 for instance, would be an improvement. However, in some instances, experience has shown that the improvement in the damping action as a whole, in preventing hunting, by tying together at *a* and *b*, more than overbalances the harmful effects of the closed secondary circuit around the commutating pole, caused by the closed damper winding. This is not necessarily always the case, the results depending upon individual and local conditions, to some extent. The same damping effect as tying together at *a* and *b* might be obtained theoretically by special proportioning of the damper on each pole, but, in some cases, especially on 60 cycle machines, space requirements do not permit such proportioning of the damper, so that it may prove better, to tie the dampers together at *a* and *b*.

A new condition also developed in connection with self starting of commutating-pole rotaries. In the older 60 cycle rotaries, starting motors were rather commonly used, due, not to the inability of the rotary to start itself, but to the effect of the large starting current upon the relatively small generating plants of those days. Later practice tends strongly toward self-starting, except in special cases. There are some very considerable advantages in this self-starting, and at the same time, there are some disadvantages, especially in the 60 cycle rotaries. The greatest advantage lies in the rapidity with which the rotary can be started from rest and brought up to synchronism, together with the fact that no synchronizing devices are required. With the old starting motor, the machine had to be brought to synchronous speed and then thrown in step. This was more difficult with 60 cycles than with 25 cycles, and self-starting eliminates this trouble. On the other hand, while starting and accelerating, the rotary converter is purely an induction motor of a rather crude sort, and will take a relatively large starting current—in some cases approximately full load current from the line—and this current is at very low power factor; that is, at least, 90 percent to 95 percent of it is purely wattless. When starting a large capacity rotary, this will represent a relatively large inductive load thrown suddenly on the power plant.

However, the new condition which developed with the advent of commutating poles, lies in sparking, and not in the starting current. As the rotary converter at start acts like an induction motor, it has a rotating magnetic field flux set up, which travels around the armature. The armature coils short-circuited by the brushes form secondaries to, or are cut by, this field, and therefore have relatively large e. m. f.'s set up in them, which develop large local currents. The e. m. f's set up in the short-circuited coils are usually somewhat greater in the 60 cycle rotaries than in 25 cycle, due primarily to the fact that there are usually fewer conductors in series for the normal voltage of the machine, and therefore the normal voltage per conductor is relatively higher than in the 25 cycle rotary. In consequence, at start, assuming that similar voltages are applied for starting both 60 and 25 cycle machines, the relative voltage per conductor generated by the rotating field set up by the armature winding will also be higher in the 60 cycle rotary. Also, the number of commutator bars covered by the brush will usually be greater on the 60 cycle rotary.

In consequence of these two conditions, the short-circuiting action of the brushes and the sparking will be worse on the 60 cycle rotaries, but it is liable to be excessive on all large machines.

With the advent of the commutating-pole rotary converter, a still more difficult condition has been encountered in self-starting, namely, that the flux conditions in the zone of commutation of the short-circuited coils are materially higher than in the non-commutating-pole machine. In the latter type, while the short-circuited coils cut an alternating flux and therefore have local currents set up in them, these coils, in commutating or reversing these currents, lie midway between the poles, and therefore in the region where the conditions of reversal are easiest. But in placing the commutating pole directly over the short-circuited coils, the conditions of reversal of the short-circuited current are made much more difficult during starting. In consequence, during starting and accelerating, the sparking conditions in the commutating-pole rotary, both for 60 and 25 cycles, are much worse than in the older non-commutating-pole type. In fact, in the larger machines, the conditions are so bad that it has been found necessary to add brush lifting devices which will lift all the brushes but two, during starting and bringing up to speed. This is an added complication, but it is offset, to some extent, by the fact that, with the brushes lifted, there is no sparking at all, and therefore the commutator does not suffer at all during the operation of starting.

In the earlier 60 cycle rotaries, the question of variable voltage came up in connection with 250 to 300 volt machines. The general means of voltage variation in these machines was almost entirely by means of induction regulators, or step-by-step transformers. It is only in very recent years that the self-contained units, such as the synchronous booster rotaries, and the regulating pole type, have been brought forward. For 60 cycle, the synchronous booster appears to be the only really practical method, due largely to limitations in design and in space requirements. If commutating poles are to be used, then the regulating pole type of machine, with main and auxiliary poles, in addition to the commutating poles, requires a very crowded design of field, unless a larger pole pitch is chosen than in the synchronous booster machine, in which there are only the commutating and the main poles.

When synchronous boosters are used with commutating poles, the problem of proper adjustment of the commutating-pole

strength, with varying loads and voltages, comes in. This has been treated before rather fully in a paper before the association, and nothing further need be said, except that this problem of adjustment is just as pronounced in 60 cycle machines as in 25. Where the range of voltage is relatively small—say, never exceeding 10 percent up or down—it is practicable to so proportion the commutating-pole windings that, without any automatic or hand-adjusting devices, good commutation can be obtained over the whole working range. However, if materially higher voltages are needed, such as 15 percent to 20 percent up or down, practice indicates that some auxiliary device is required for automatically, or by hand, adjusting the field strength at the extreme condition, which appears to be at no-load with maximum boost or buck. For this condition, an automatic device has been developed, which, when the main current falls to a relatively low value—say, one-fourth full load—automatically short-circuits that part of the commutating-pole winding which is in series with the booster field. The same operation cuts into the circuit a resistance equivalent to the section of the winding cut out. This latter is a necessity, due to the fact that any variation of the resistance of the booster field circuit will vary the amount of boost or buck, and thus affect the main voltage of the machine. Any automatic device therefore should hold the resistance of the booster circuit constant. Such devices have been installed on a number of synchronous booster, commutating-pole type machines. They can be located at the rotary, and, being purely automatic in their action, require no attention from the switchboard operators or anyone else. As such a device operates only very infrequently, but at fairly regular intervals, such as once or twice a day, it is not liable to wear out due to excessive operation, or to stick due to non-use. Experience has shown that, except for extremely wide ranges in D. C. voltage, only one step is needed in such automatic device.

60 cycle rotary converters are now being manufactured in relatively large capacities, such as 1000, 1500 and 2000 kw for 270 volts with synchronous boosters, and up to 2500 kw for higher voltages. Larger capacities, for either voltage, can be constructed without difficulty, and with as good performance as in the capacities mentioned. The modern 60 cycle rotary converter for either 270 or 600 volts, is approaching very close to the 25 cycle rotary in its general characteristics, such as efficiency etc. In commutation, it can be fully equal to the 25 cycle. In general relia-

bility, the modern machine is far ahead of the older types. This development of the 60 cycle rotary therefore removes one of the most serious handicaps formerly encountered by the large 60 cycle generating systems.

IRON LOSSES IN DIRECT-CURRENT MACHINES

FOREWORD—This paper was presented before the Schenectady Section of the American Institute of Electrical Engineers, March, 1916, before an audience composed almost entirely of engineers of the General Electric Company. It is principally of interest to designing engineers, in general, and it brings out some of the problems actually involved in an analysis of the loss conditions occurring in direct-current machinery. Certain explanations of eddy current losses, due to saturation of the armature teeth, are brought out here for the first time, the author believes, and some approximate methods of calculating these losses are given. In fact, a careful study of this paper will indicate wherein the calculation of the no-load losses in any direct-current machine is, necessarily, more or less empirical, while the conditions with load are very much worse.

After the presentation of this paper, there was a general discussion, largely of a constructive and educational nature, which appears in the Proceedings of the American Institute of Electrical Engineers.—(ED.)

IRON loss is a general term to cover a number of losses, of various kinds, which, by the nature of the tests, are included in one set of measurements and which, in reality, should be known as core loss. The term has been used so promiscuously, without indicating what it really includes, that many have come to believe that it means the true iron loss and nothing else. In fact, however, the true iron loss, due to magnetic conditions in the iron itself may be, in many cases, only a moderate percentage of the total core loss. What might be called the normal hysteretic and eddy current losses in the iron itself may be overshadowed by abnormal losses due to improper flux distribution and other causes consequent upon incorrect proportioning of flux paths and directions. Also, usually no distinction has been made between the losses simply located in the iron itself, and those directly due to magnetic conditions. Furthermore, the losses in non-magnetic parts adjacent to the iron, and lying in the flux paths, may, in some instances, even exceed the total losses in the iron. The readily practicable methods of measuring the core losses show only their sum and there is no true indication of the relative values of the various com-

ponents. To separate the total core loss into its various components, except by complicated and expensive laboratory methods, appears to be almost impossible However, it is possible to indicate the various components and their probable causes, and in some cases they can be segregated very crudely by calculation.

In most rotating machinery the calculation of the individual elements, which make up the total core loss, is necessarily only approximate, in commercial apparatus. This is due partly to the fact that there are many possibilities of variation in loss on account of conditions of manufacture and materials, as will be described later. This is evidenced by the fact that two machines, built at different times from the same drawings and the same tested grade of materials, will ofttimes show materially different core losses. If two such machines vary twenty-per cent from each other in core loss, it is obviously impracticable to expect any refinement in calculation closer than twenty per cent Even if we always could come within twenty per cent by direct calculation and could place any great reliance upon the results, it would be a great step ahead, in certain types of apparatus. In the discussion of the various losses and their causes, given throughout the following paper, it will be shown why it is impracticable to calculate, with any exactness, certain of these losses.

In separating the total core loss into its components, two principal classifications of losses may be made. One of these is eddy current loss, either in the iron laminations themselves or in other conducting parts wherein e.m.fs are generated during rotation. Such e.m.fs. will set up local currents where closed paths are possible, and if such paths are in the laminations themselves, instead of in neighboring solid parts, it is simply incidental Eddy current loss in the laminations is, therefore, not a special kind of loss, and it should rightly be classed with other eddy losses in the machine.

The second class of losses includes those due to changes in the magnetic conditions in the iron itself; these are known as hysteresis losses. These latter are dependent upon the material itself and not its structure. Lamination is primarily for increasing the resistance in the eddy current paths and not for the purpose of affecting the hysteresis. In fact, lamination may increase the hysteretic losses, for a given volume of material

The principal object of this paper is to show causes for some of the principal losses. These are usually related to two sets of frequencies, namely, the normal frequency (revolutions per second times number of pairs of poles), and some very high frequency, dependent upon the number of slots, commutator bars, etc. The hysteretic losses are undoubtedly affected by these higher frequencies but apparently not to the same extent as the eddy losses. These high-frequency losses are liable to be present in most classes of rotating machines, while in some instances they may overshadow all other losses Certain of them are characteristic of certain types of machines only, while others are liable to be present in any type of rotating machine

In most classes of rotating machines, only the no-load core losses can be measured with any accuracy by ordinarily convenient methods of measurement. However, if the various components of the no-load loss can be approximately determined, then it is possible to indicate in what way these same components will be affected by load. A quantitative determination of the component losses with load is, however, very difficult to determine except in a very few classes of machines.

In direct-current machines the principal no-load armature core losses are the hysteresis loss in the iron, eddy losses in the iron and copper, and eddy losses in other adjacent conducting parts, which may be seats of e m.fs. The relative values of these losses are dependent upon many conditions. In a thoroughly well designed machine the eddy losses in the copper and any other parts than the iron should be relatively small compared with the iron loss proper. Again, the proportion of hysteresis to eddy loss in the iron itself depends upon many conditions, such as the various frequencies in the machine, the grade of material, the degree of lamination, the perfection of the insulation of the laminae from each other, the distortion of the material in handling and building, the conditions of punching, treatment during assembly, grinding, filing, etc. Here, at once, so many variables appear that one cannot reasonably expect any great accuracy in any predetermination of eddy loss in the iron itself. Hysteresis loss is also affected by some of these conditions.

It is a fact well known to designers that the iron loss tables used by transformer engineers do not directly apply to rotating machinery, but that an increase, in some cases, of one hundred per cent, or more is necessary, depending upon the

type of machine. This increase is due largely to additional causes of loss which do not occur to any appreciable extent in transformers. Some of these additional losses are as follows:

(a) Handling of iron. Experience shows that well annealed armature iron will have its losses very materially increased by springing or bending If a lamination is given a decided bend, beyond the elastic limit, and then is straightened out, the loss at the part which has been bent may be increased as much as 100 per cent. This fact must be taken into account in machinery where armatures with many light teeth are used. Here it is almost impossible to prevent some abuse of the iron, especially in the teeth, which are the parts usually worked the hardest. Furthermore, tests have shown that if iron is bent, even at a small angle, and not beyond the elastic limit, the loss is materially higher with the iron in this strained condition, although the loss may return to normal when the iron is allowed to spring back to normal position. And if the iron is annealed in a curved or warped position, then when straightened out in building the strain is present, with increased loss. In building up armature cores, undoubtedly part of the iron is put under stress, especially in the teeth. Any dent in the iron, produced by hammering or otherwise, also tends to increase the loss.

(b) A second source of increased loss in the iron is due to the operation of punching. In shearing the iron a small amount adjacent to the sheared part is affected much in the same way as when iron is bent beyond the elastic limit. In transformer plates this strip next to the sheared edge represents but a very small percentage of the total volume of each plate or lamination. However, in armatures with many comparatively long narrow teeth, this sheared part may represent a relatively large percentage of the whole plate and, moreover, this is a part which often has the largest losses. But this may not have as great effect on the losses as another result of the shearing, namely, the sharp burrs which are left on the iron. These may be very small or almost negligible in appearance and yet represent quite a large percentage of the thickness of the plate. For example, a burr of two mils height, or 1/500 in., seems to be very small indeed, and yet it is about 12 per cent of the thickness of a 17-mil lamination. Dies must be maintained in very good condition to keep the burr below two mils. The effect of this burr is to bring increased thickness and pressure

at the edge of the sheets, particularly at the teeth. If the laminations are all turned one direction in building and the edges match perfectly the sheets might fit together so accurately that the burr would cause no extra thickness. But it is impossible to obtain such accuracy in practise and, therefore, the burrs of one sheet "ride" upon the surface of the next sheet, thus increasing the total thickness of the built-up iron. In practise, however, the iron is pressed down to approximately uniform height throughout. This means that the burrs carry considerable of the pressure at the armature teeth and there is more or less of a tendency to cut through the insulating film on the plates, thus increasing the eddy current losses. This is obviously a variable condition depending upon the accuracy of building, upon the condition of the dies, etc., and no method of calculation can take this loss into account with any accuracy. In small machines with low voltage per unit length of core, this loss usually is not of great importance. However, in high-speed large-capacity machines, it becomes increasingly important and in some cases special means are used for removing the burr before insulating the individual armature plates.

(c) Another source of iron loss, and one which also is beyond the scope of calculation, is found in the filing of armature slots and cores. In ideal armatures with perfect punchings and assembly, there should be no occasion for filing. However, the practise, in many cases where the armature iron does not build up with perfectly smooth surfaces in the slots, is for a limited amount of filing to be done. Usually this takes off only isolated high spots, so that the adjacent laminations are not bridged over to any great extent by the burrs due to filing. The tendency of most workmen is to file down to a nicely polished surface, whereas a coarse filing gives better results as it tends to break the laminations away from each other. Filing is most harmful in machines having a relatively high voltage per unit length of core. A milling cutter for cleaning out slots is usually worse than a file, as it produces greater burring of the edges. However, if the milling is followed by filing with a very coarse file the results may be just as satisfactory as with filing alone. Obviously, no method of calculation can show accurately the losses due to such burring.

(d) The iron losses are affected to a certain extent by pressure, that is, by the tightness with which the core is clamped.

The loss due to this is probably closely related to some of the preceding losses, such as bending and springing of plates, effect of burrs, etc. In small machines the effect of pressure apparently is of little moment, but in large very long cores it may become very appreciable. It is particularly noticeable in large turbo-generator armatures where the cores are very wide. In such machines, in attempting to draw the core down to a sufficiently solid condition as a whole, the parts next to the end plates are liable to receive abnormal pressure, with consequent increase of loss in those parts. For this reason, it is the practise in some cases to add an extra separation of paper at frequent intervals near each end of the core. Experience shows that this equalizes the losses and temperatures very materially. That this is due to undue pressure and not to stray field or other conditions, is indicated by the fact that when high temperatures are found in the iron, at each end of the core, very often the condition can be relieved by simply lessening the pressure to a comparatively small extent. The writer has known cases where the temperature in the end sections of the iron has been reduced 30 to 50 per cent by "easing off" the end plates. The total loss in the core may not be reduced very much, for the reduction in pressure usually affects only the end sections to any great extent. Presumably this loss is due to increased contact between the adjacent plates, possibly from the burr, but not entirely so, for similar results have been found in some cases where the burr had been fairly well removed before enameling the plates. The character of the enamel coating used for insulating purposes also has something to do with this.

In connection with pressure, the effect of heating of the core may be considered. Cases have been noted where the effect of high temperature of the core has been to increase the pressure between the laminations, due to expansion. This in turn increased the loss and thus still further increased the temperature. This effect has not been uncommon, to a minor extent, but a few cases have occurred where the combined pressure and temperature cumulatively have resulted in excessive core temperatures. In one case which the writer has in mind, a certain large machine operated for about two years without any noticeably high temperature in the core. Then, in a comparatively brief time, it showed evidence of increasing temperature until finally an entirely prohibitive tempera-

ture showed at one place. Examination showed that the core was very tight and all evidence indicated that increased temperature was causing increased pressure and thus further increasing the loss. In this machine, fortunately, the construction of the armature core and winding was such that the end plates could be released very easily about $\frac{1}{4}$ in. on each end. This was tried as an experiment and the temperatures all returned to the former normal of about 30 deg. cent. rise. As an interesting side issue, it may be mentioned that on this machine the armature teeth at each end of the core had been breaking off, although stout brass supporting fingers had been used. Apparently under the increased pressure, due to heating, the fingers would be bent away from the core, thus releasing the tooth laminations. Repeated tightening of the brass fingers did not relieve this condition. However, when the end plates were released $\frac{1}{4}$ in. at each end of the core, the brass fingers were then sprung in against the teeth and afterwards remained in position so that no breakage of tooth laminations was ever reported afterwards.

Obviously, with losses dependent upon pressure, no extreme accuracy in calculation of such losses is possible. However, in moderately small size machines, and especially in those of very moderate frequency and of very low voltage per unit length of core, the effect of pressure is not serious, within a moderate range of practicable pressures.

(e) Another source of iron loss, but which is not in the armature core, is that of the pole face, due to the tufting or bunching of the flux between the field pole and the armature teeth, where slotted armatures are used. Obviously, with all other conditions the same, this pole face loss will depend upon a number of variables in the lamination of the material itself. The effect of burrs from punching, the burring over of the surface due to turning, the effect of pressure, etc., all appear in the pole face loss. Therefore, it is evident that great accuracy in the calculation of such loss is impossible, in commercial apparatus. There are other conditions that affect this pole face loss which will be considered later under this subject.

Armature Ring Loss. The true iron loss in the armature ring is dependent upon the total flux per pole, distribution of flux, rate of change of flux, etc. The problem is much complicated by the fact that the flux distribution in the ring usually

is not uniform, that is, certain parts of the core have higher maximum densities than other parts However, in ordinary practise the core densities used are relatively low, so that the losses can be approximated by averaging the inductions in certain parts. However, the rate of change of flux in the ring is dependent, to a certain extent, upon the flux distribution in the air gap and armature teeth, and this introduces some error, always in the direction of increased loss.

The distribution of flux in the armature ring is also dependent upon the effective length of the various flux paths. These latter will naturally depend upon various conditions, such as the number of poles, diameter of armature; flux distribution in the air gap and teeth, etc. Therefore, any method which does not take this distribution into account is necessarily only approximate. However, in practise there are so many other variables, as already described, in connection with manufacturing conditions, such as burring, filing, etc., that empirical rules have been developed, based upon numerous tests, which approximate the armature core loss in a standard type of machine about as accurately as any attempt toward exact calculation.

Armature Tooth Losses at No-Load. Apparently the flux densities in the armature teeth can be calculated with more accuracy than in the various parts of the core, for in the teeth the fluxes are limited to fairly definite paths. Therefore, exclusive of the losses due to manufacturing conditions, as already described, the tooth losses can be fairly accurately calculated, probably with much greater accuracy than many other losses, as will be described. The tooth losses may be considered further as follows:

The flux density in each individual armature tooth passes through a cycle, indicated by the shape of the field form. With the field form of the shape illustrated in Fig. 1, the tooth density will be a maximum at A, and this density will remain practically constant as the tooth moves toward C until the point B is reached. It will then decrease as the ordinate of the field form curve decreases and will reach zero value at C. The cycle of flux change is not sinusoidal, and therefore, the actual tooth iron loss should not agree with that represented by the usual iron loss curves based upon sinusoidal changes in induction. The difference, however, may be relatively small in the ordinary types of machines. The error may be

taken care of by some suitable correcting factor, which of course, will be only approximate for the average case

The density in the armature teeth is involved in the iron loss This density is not uniform over the entire depth of the tooth, with the usual parallel-side slots, for the section of the tooth tapers off. This difference of section, in small diameter machines, may be very considerable. However, a higher density at the base of the tooth, tending to give higher iron loss, is compensated for, to some extent, by the reduced volume of material. In consequence, the mean section at some point from one-half to two-thirds the way down the tooth may be taken and the mean density and volume of material, based upon this section, may be used for approximating the iron loss. The accuracy of this method will be dependent, to some extent, upon the actual density used. For instance, if both the minimum and maximum densities in the tooth are relatively low, then the loss calculated for the mid-point density, at the mid-point section, will be closer to the true loss than if the maximum density is excessively high.

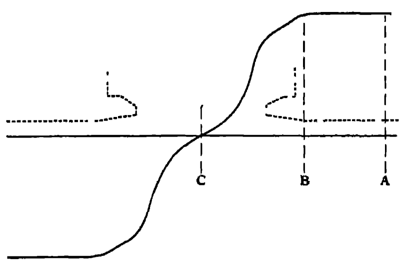


FIG. 1

Armature Copper Eddy Current Loss at No-Load. There may be a number of eddy current losses in the copper, some of which are of a minor nature. However, there may be two relatively large losses, depending upon the design of the machine. One of these is due to the flux from the field poles entering the armature slots and cutting the conductors. This is, to a certain extent, a function of the saturation of the tops of the armature teeth. It is also dependent upon the width of the slot opening compared with the iron-to-iron clearance. At first thought, one would say that the larger the air gap the more would the lines from the pole pass into the tooth top. However, the opposite is the case, for the larger the gap, the nearer do the lengths of paths into the slot approach to the iron-to-iron clearance, in percentage.

In moderate size machines with relatively small air gaps and moderate slot widths, the eddy current loss from fringing into the top of the slot is comparatively small, and, as a rule,

no special precautions need be taken to minimize it. This particular loss is usually greatest in high-voltage, large-capacity turbo-alternators, where relatively wide slots, up to 1 5 in. or more, may be used, and where the air gaps are very large. In such cases lamination of the top conductors to avoid eddies from this cause may be desirable.

The second source of eddy current loss in the copper, which is liable to be larger than all others combined, is due to the peculiarities of flux distribution in the armature teeth. Let Fig. 2 represent the magnetic conditions in a given machine. It is evident from this figure that under the central flat part of the field form, the armature teeth are worked at a uniform induction, assuming that there is no field distortion. However, at the edges of the pole the tooth density decreases slightly. If the saturation of the teeth under the flat part of the field form is very high (materially above 120,000 lines per sq. in.), the ampere-turns required to magnetize the teeth may be very considerable. However, at the edge of the pole a comparatively small decrease in the flux density in the teeth (15 to 20 per cent) will mean a relatively enormous decrease in the ampere-turns for the teeth. For instance, the tooth *c* in Fig. 2, under the central flat part of the field form, may require 2000 ampere-turns, while the next tooth *b*, under the pole edge, which is worked at possibly 20 per cent lower density, may require only 10 to 20 per cent as many ampere-turns. Assuming such conditions, then the magnetic potential at the top of tooth *c* will be higher than that at the top of *b* by 1600 to 1800 ampere-turns. Therefore, under this condition there will be a very considerable flux across the slot between *c* and *b*. A little earlier or a little later in the rotation this flux across this slot will not exist to any extent, for the ampere-turns for *b* and *c* will then both be comparatively low or very high, while the difference between them will be small. In consequence, near each pole edge, there is a very rapid rise and fall of flux across the armature slots. This is illustrated in Fig. 2.

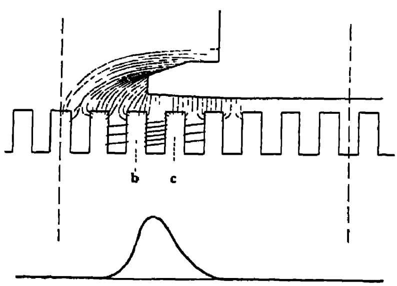


FIG 2

Obviously, the armature conductors lying in the path of

this flux will be the seat of e.m.fs. which will tend to set up local currents, the value of which will be some function of the e m.f. producing the current, of the dimensions of the conductor, etc If the flux across the slot is large, this e.m.f. may also be considerable, for the rate of this flux change will be high compared with the normal frequency of the machine. As the e.m f. generated is a function of the maximum difference between the ampere-turns required for two adjacent teeth and as the loss in any given case will vary as the square of the e.m f , obviously the loss in one slot will vary as the square of the maximum difference between the ampere-turns of two

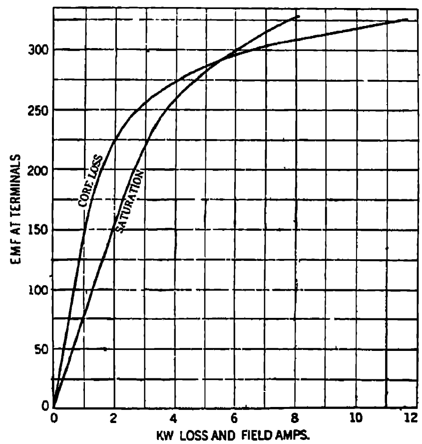


FIG. 3

adjacent teeth. At very high saturation, the maximum difference between the ampere-turns required for two adjacent teeth may be relatively high and the loss may be correspondingly great. Due to the shape of the permeability curve of steel at very high saturation, the difference between the ampere-turns of two adjacent teeth may increase faster than the square of the terminal e.m.f. Therefore, the eddy current loss due to this cause may increase faster than the *fourth power of the total induction per pole.* Evidently, therefore, it is desirable to keep these eddy current losses at a low value at no-load, for the high tooth ampere-turns under the distorted field conditions of full load will tend to increase the percentage of these losses very greatly. Fig. 3 shows a characteristic core loss

curve for a generator in which the copper loss, due to the above cause, is very large at the higher e.m.fs.

Several years ago, the writer spent considerable time in attempting to determine the value of this eddy current loss at no-load. Neither sufficient nor entirely satisfactory data were available. From the data at hand, the following empirical formula was derived, which appeared to accord fairly well with the facts in a number of cases which were worked out. This formula applies, however, only to windings with two conductors in depth per slot. This formula for the loss in conductors is

$$\text{Watts loss} = \frac{180\ V_c\ R_s\ p\ (1000 + a)^2}{10^8}$$

a = Maximum ampere-turns for one tooth.
V_c = Total volume of copper, in cubic inches, in one slot.
R_s = Revolutions per second.
p = Number of poles.

The values for the watts eddy current loss in the copper were approximated by taking the iron loss curves at the lower e.m.f. values (where the above eddy current loss would be very low), and then projecting them for the higher values according to the laws which the iron loss alone should follow. The difference between this corrected iron loss and the actual test curve was assumed to consist largely of eddy current loss. As this difference usually increased very rapidly at higher inductions, the above assumption was in line with the preceding statements that this eddy current loss may increase much more rapidly than the square of the flux. In this determination obviously the pole face loss would have to be taken into account. This was taken care of as far as possible, by tests with relatively large air gaps, the pole face loss thus being very small.

It may be noted that in the above empirical formula, the ampere-turns for one tooth under the maximum field has been used, instead of the maximum difference between the ampere-turns of two adjacent teeth. However, the tests indicated in general that the maximum difference was approximately proportional to the maximum ampere-turns in one tooth and, therefore, it was simpler to use the total turns for one tooth. Also, where the total tooth ampere-turns are tapered off over

several teeth, the difference between the ampere-turns for adjacent teeth is reduced, but more slots and more copper is involved, whereas the empirical formula includes only the copper for one slot. Various attempts were made to include all the different factors, such as ampere-turns across each slot, number of slots, number of conductors involved, counter magnetomotive force of the eddy currents, etc., but none of the resulting formulas gave as consistent results as the above. It must be admitted that this formula is an extremely crude one, but it happened to fit most of the cases that the writer was able to analyze. In deriving this equation, it was found that if the loss was assumed to vary directly as the square of the tooth ampere-turns, then it would be too great at very high tooth saturation. At high tooth densities, the flux across the slots, at the pole edge, is distributed over several successive slots, so that the maximum difference between the ampere-turns of two adjacent teeth bears a lower proportion to the ampere-turns for one tooth. Also, at very high tooth densities there is more or less fringing of flux down through the slot, in parallel with the tooth flux, and this makes the determination of the actual tooth flux difficult. In the formula, therefore, the term $(1000 + a)^2$ is used in place of a^2 to take care of these conditions. This term, however, is obviously wrong, in that it indicates a loss when the tooth saturation is negligible. However, this loss under low saturation usually works out from the formula to be of comparatively small value, so that the error is not of much importance.

A modified formula, which agrees with the above fairly closely at high saturations, but gives no loss at zero saturation, is the following:

$$\text{Watts loss} = \frac{135\ V_c\ R_s\ p\ (4000 + a)a}{10^8}$$

The following table shows the comparison of the copper eddy loss compared with the calculated loss by the first formula above, for a number of machines. It will be noted that the agreement is not particularly close, but possibly as good as could be expected, considering how the test losses were derived. It may be stated that these were all comparatively old types of machines, for in recent years great pains have been taken to eliminate large eddy losses of this character, so

that it was necessary to go to old machines in order to obtain exaggerated cases.

Kilowatt rating	Terminal e m.f	Rev per min	No of poles	Calculated ampere turns in teeth	Eddy loss estimated from test curve; kw	Eddy loss calculated from formula; kw
340	600	685	6	1400	2 7	3 4
"	700	"		3000	10 0	9 7
500	600	225	10	2500	7 5	6 15
"	625	"		4000	17 5	12 5
750	250	514	10	1200	1 5	2 76
"	320	"		7200	32 0	39 3
750	550	514	8	1500	4 5	3 3
"	700	"		7000	33 0	36 5
1000	250	514	12	600	2 5	2 2
"	330	"		6000	50 0	41 3
1000	600	514	10	1225	4 5	4 6
"	700	"		2380	10 0	11 3
2000	575	300	14	3000	12 0	7 1
"	675	"		7000	36 0	28 2

Pole Face Losses at No-Load. It has long been known that, with open slot armatures, there are liable to be considerable losses in the field pole faces due to bunching of the magnetic flux from the armature teeth to the pole face, the armature teeth thus acting as small poles of an "inductor" type alternator, of which the pole face, to a small depth, serves the function of the armature core.

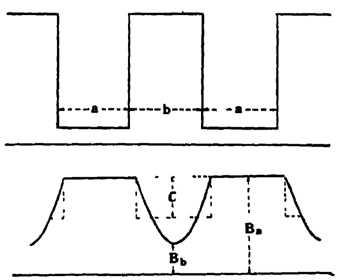


FIG. 4

While the effect of this "inductor pole action has long been known, the amount of loss due to it has frequently been underestimated, especially in machines with relatively small air gaps compared with the width of the armature slots.

The following crude description will illustrate the extent of the variations in flux in the air gap due to the open armature slots. In Fig. 4, *a* represents the width of one armature tooth and *b* represents the width of one armature slot. Let *g* represent the single air gap (iron to iron).

In the lower diagram, which represents the flux distribution in the air gap, let B_a represent the flux density in the air gap

under the armature teeth and B_b the minimum flux density corresponding to the center of the slot.

Then, $a \times B_a$ = the total flux under one tooth, for unit width of core, and $b\ (B_a - B_b)\ c$ = the total decrease in flux for the space covered by one slot represents the average height of the curve *def* in Fig. 4. If this curve be assumed to be sine shaped, then c would be 0.636 Any other shape which would be likely to be found in practise would not be far from this value. A V-shape, as one extreme, would give c = 0 5 while a circular shape, as the other extreme, would give c = 0.784. Apparently the value would lie somewhere between these two extremes.

In calculating the effective gap from the above diagram and assumptions, the following equation would be obtained·

$$\text{Increased gap } g' = g \times \frac{(a+b)\ B_a}{(a+b)\ B_a - b\ (B_a - B_b)c}$$

$$\text{Or, } g' = g \times \frac{1}{1 - \dfrac{b\ (B_a - B_b)\ c}{(a+b)\ B_a}} = g \times \frac{1}{1 - \dfrac{(b)\ (B_a - B_b)\ c}{(a+b)\ (B_a)}}$$

The resemblance of this equation to Carter's well-known equation for the increased air gap may be seen at once.

$$\text{In Carter's equation, } g' = g \times \frac{1}{1 - \dfrac{b\ k}{a+b}}$$

Comparing these two formulas, it is evident that k =

$$\frac{(B_a - B_b)\ c}{B_a}$$

An extremely close approximation to k can be obtained from the empirical formula $k = \dfrac{\frac{b}{g}}{5 + \frac{b}{g}}$ This holds closely

to Carter's curve over almost the entire range. Equating the above two values of k, we obtain the equation

$$\frac{B_a - B_b}{B_a} = \frac{1}{c} \frac{(b)}{(5\,g + b)}$$

Or,
$$\frac{B_b}{B_a} = 1 - \frac{1}{c} \frac{(b)}{(5\,g + b)}$$

This gives the ratio of the flux density at the middle of the slot to the flux density under the tooth.

As an example of what these relative values may be, assume that $a = b$, or the slot width = the tooth width, and that $g = 0.25\,b$, which is extreme for large a-c. or d-c. generators, but not unusual for induction motors. Assuming $c = 0.635$, then $\frac{B_b}{B_a} = 0.3$, or the density under the middle of the slot is only 0.3 of that under the tooth. With these same values, the value of g' becomes 1.2859, or the gap increase is 28.5 per cent, which is not unusual for some machinery. Obviously, a variation in the flux density at the pole face of 70 per cent should tend to give high iron losses in the pole face itself. In fact, some of the inductor type alternators which were in common use a few years ago did not give variations in armature flux materially better than indicated by the above value. Such proportions as the above example would, therefore, be fairly good for an inductor alternator.

The above analysis is given simply to furnish a means for determining the possible variations in the flux density which may be obtained with open slots. This gives a much better conception of the problem than can usually be obtained directly from Carter's formula for the increased length of gap. It also gives a good idea of the possibilities of tooth losses in those cases where the teeth of one element or member of a machine alternately pass under the teeth and slots of the other member.

Considerable work has been done at various times to determine the pole face losses due to open armature slots. The difficulty in determining a workable formula is very considerable, as there are many conditions which may directly or indirectly affect this loss. For example, the thickness of the

laminations, or the material in the pole face, may have an influence. Any general formula for this loss would require different constants for different types of pole faces. One formula for this loss has been given by Professor C. A. Adams and his associates.* The formula is very complex and somewhat difficult to use.

A much simpler formula for laminated pole faces is as follows, for 0 031-in. laminations:

$$\text{Watts loss} = \frac{75\, b\, E^2}{C_f\, W_s^2\, g\, L} \sqrt{\frac{S_c}{R_s\, g}}$$

E = Generator voltage.
b = Width of slot.
g = Single air gap (iron to iron).
W_s = Armature wires in series.
L = Width of pole face.
C_f = Field form constant.
S_c = Total slot space = width of slot × No. of slots.

It is very difficult to obtain any reliable data on pole face losses alone, for other core losses are liable to be included in any tests. Variation of air gap, with everything else in the construction unchanged, gives a partial measure. However, this changes the field form somewhat and thus modifies the

Pole Face Losses, by Comfort A. Adams, A. C. Lanier, C. C. Pope and C. O Schooley. PROC. A. I. E. E., July, 1909, page 1151.

$$W_p = S_p \times p \times 0.000462 \left(\frac{B_g}{10^4}\right)^{2\ 4} \times \left(\frac{v}{10}\right)^{1.55} \times q^{1.5} \times \frac{1}{t_p}$$

W_p = Pole face loss.
S_p = Section of one pole face (average section where the density is B_g).
p = Number of poles.
0.000462 = Constant for $\frac{1}{16}$-in. laminations.
B_g = Density in the gap over the section S_p.
v = Velocity of the armature surface in feet per second.
q = Ratio of width of slot to air gap.
t_p = Tooth pitch in inches.

tooth saturation and the tooth and eddy losses, to a certain extent, thus rendering doubtful the pole face component.

The above formula is necessarily approximate and applies only to laminated pole faces. The effect of cutting away part of the laminations in order to produce high saturation at the pole face is not included. However, it is possible that this may not influence the loss to any great extent. The greater part of the loss is represented by eddy currents, and cutting away part of the laminations will tend to break up the losses between plates and this may compensate to a considerable extent for the higher densities in the remaining plates It is hoped that some time in the future more complete data may be obtained, over a sufficiently wide range of conditions, to cover the practical range of ordinary design.

The following table covers a number of machines with adjustable air gaps in which the pole face losses were worked out according to the above formula. Also, the total calculated and the total test losses are given, to indicate the agreement in a general way. The writer is perfectly willing to admit that he believes that the fairly close agreements between some of the calculated and test totals are largely accidental, and they should not be taken as proof of any great accuracy of the methods.

It is obvious from this table that the pole face losses may be comparatively high in some cases, provided the formula is reasonably correct. Evidently, if these losses could be calculated with any great accuracy, the design of the machine might be considerably modified, compared with more recent practise, with advantageous results. The pole face losses will evidently be greatly increased by field distortion when the machine is carrying load. Eddy currents in the copper are also affected by field distortion, and a correct method of calculating both the eddy current and the pole face losses with various loads should lead to considerable modification in the proportions of d-c. machines, in general.

Stray Losses. Under this heading may be included a number of no-load losses which are usually of a minor nature. Among these may be included secondary losses in the armature winding due to unsymmetrical cross-connections or unbalanced voltages in parts of the winding which are connected in parallel. There are various possibilities for losses from this source and, in consequence, it is always advisable to use armature wind-

Kw.	E.m.f.	Rev. per min.	No. of poles	Single air gap; inch	No. of slots	Width of slots; inch	Tooth ampere-turns	Pole face watts	Calculated core losses: Copper watts	Calculated core losses: Core watts	Calculated core losses: Teeth watts	Calculated core losses: Total watts	Total test losses watts
200	250	1150	6	0.156	64	0 406	1635	2060	3660	1200	2500	9420	8500
				0.125			1887	2870	4400	1200	3000	11470	11600
200	250	1200	6	0.25	72	0 391	275	975	895	670	1450	3990	3800
				0.125			395	2200	1075	670	1650	5595	7300
750	250	514	10	0 25	200	0.312	2520	2530	7010	2560	5100	17200	19800
				0.1875			2820	3860	7410	2560	5320	19150	22000
750	550	514	8	0 375	200	0.328	2650	1190	7375	1945	3780	14290	14000
				0.250			2840	2210	7770	1945	4000	15925	15550
1000	600	514	10	0.281	140	0.625	2050	6380	15060	5290	6200	32930	30800
	700			0.281			3750	8680	36500	8320	7800	61300	62500

ings which are as symmetrical as possible. Also, the arrangement of the winding should be such as always to generate balanced e.m.fs. in parallel circuits. This condition is not infrequently overlooked in the design of direct-current machines.

A second cause of undue loss in the armature winding may be occasioned by short-circuiting one or more of the armature coils under an active field. The brushes may be shifted from the magnetic neutral point so that some of the armature conductors are short-circuited under the main field flux; or the neutral point may be so narrow and the brush so wide that some of the armature turns are short-circuiting in an active field, even when the brush is set for the no-load neutral. An armature winding which is considerably "chorded" in a field with a narrow neutral point may have two sides of a coil short-circuited in fields of the same polarity. The e.m.fs. in the two sides of the coil should, therefore, balance each other if the brush is set at the true neutral. However, if the brush short-circuits several coils or turns, obviously only one of them can be at the true neutral and have balanced e.m.fs. set up in its two halves. The other turns may have more or less local current in them, which may be a source of considerable loss.

A third condition may occur when there are considerable pulsations in the reluctance in the air gap under the main poles as the armature teeth move under the poles. This varying reluctance usually gives varying main flux and at a relatively high frequency. The armature coils short-circuited by the brushes will act as secondaries to these pulsating fluxes and in consequence there may be some loss in the short-circuited coils due to this cause. Any solid parts of the yoke or poles may also have losses due to this cause. Usually, however, such losses are small.

A fourth source of loss may rise from stray fluxes from the main fields to the armature, which do not pass through well laminated parts of the armature core. For instance, the ventilating spacers may be so dimensioned and shaped that eddies can be set up in them. Also, the finger plates at each end of the core, the end plates, etc., may carry light fluxes which produce some loss. Bands on the armature core or at the ends may also be the seat of e.m.fs. and will have some loss in them. These losses are difficult to determine, and, in practise, should be eliminated as far as possible.

Full Load Losses

It is evident from the foregoing that the no-load core losses are dependent upon so many variable conditions that there can be no great accuracy in predetermining such losses unless all the details of construction, material, treatment, etc., are known for each individual machine. The impossibility of accurate calculation is shown by the fact that the individual machines built on the same stock order will vary considerably from each other, especially in certain types.

While the no-load losses are difficult to predetermine, the full load losses are still much more difficult to calculate, as will be shown in the following rough analysis. Here, the effects of flux distortion by the armature magnetomotive force tend to exaggerate the pole face losses and those in the armature copper; which are the two relatively large losses which are most difficult to calculate at no-load. Also commutation and brush losses, due to load, now enter into the problem. The individual core losses may be considered briefly as follows:

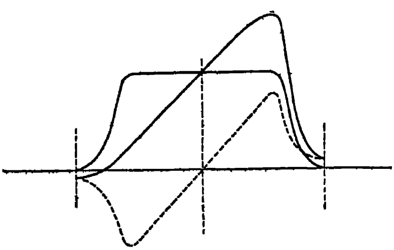


Fig. 5

Armature Ring Loss, with Load. This loss should not change greatly with load, provided the total flux at load is practically the same as at no-load. Under this condition a variation in the distribution of this flux is about the only factor which should produce any material change in loss. The full load field form may be illustrated by Fig. 5. It is evident from this figure that the flux is now crowded toward one pole edge and, therefore, the major part is concentrated in a narrower space. The average length of the flux path may, therefore, be somewhat greater than at no-load, but in some cases this may tend to distribute the flux more uniformly through the depth of the ring. However, where the flux enters the core at the base of the teeth there will be slightly more crowding and, therefore, somewhat increased loss. Taking everything into consideration it would appear that, in general, the armature ring loss can be considered as practically constant with constant total flux and speed, independent of the variation in load.

In variable-speed and adjustable-speed d-c. machines, the armature ring loss may vary over a wide range due to changes in total flux and speed. Such cases are difficult to calculate with any degree of accuracy, although no more so than other losses in the same machines.

Armature Tooth Loss, with Load. As shown by Fig. 5, the tooth flux density at one edge of the pole is decreased and at the other edge is increased when the field flux is distorted by the armature magnetomotive force. The increased density in the armature teeth means increased iron loss and, if the distortion is very great, the increase in tooth loss may be very large, being in some cases even doubled or trebled, compared with the no-load tooth loss. No direct rule can be given for the calculation of this loss, except that it may be determined approximately by calculating the flux distribution with oad and thus determining the flux densities in the teeth.

In variable-speed and adjustable-speed machines, particularly in the latter, the tooth loss with load will be affected very considerably by changes in both speed and total flux. In variable-speed machines of the series type, reduction in speed usually accompanies increase in total flux, so that, as regards the losses, one effect partly neutralizes the other, so that the increase in tooth loss with load may be less than in a constant-speed machine. In adjustable-speed machines, however, especially in those of constant horse power and constant voltage, the tooth losses will vary over a very wide range with change in speed. Here, the armature magnetomotive force is constant (assuming a constant horse power) and the field flux is varied from a maximum value at lowest speed to one-quarter value at four times speed, assuming a four-to-one range. The total flux, therefore, varies inversely as the speed and the two effects should nearly compensate each other, as regards losses, if it were not for the variation in flux distortion. At lowest speed, with considerable saturation in the pole horns and armature teeth, the armature magnetomotive force, even if relatively large compared with the field magnetomotive force, may not produce very large distortion, so that the tooth loss is not increased excessively over the no-load tooth loss. However, as the field is weakened, the armature magnetomotive force remaining constant, the distortion is relatively increased, so that the peak value of the distorted field may remain almost constant in height. As the armature tooth losses are dependent

upon the peak value of this field, then obviously the combined effect of this field and the increase in speed will mean very greatly increased tooth losses. With very low field magnetomotive force, the distortion may be so great as to give a double peak, as indicated in Fig. 6. This double peak gives, to some extent, the effect of a double frequency and thus further increases the loss.

Eddy Currents in Copper. When the field form is distorted, with load, the ampere-turns in the teeth at one pole corner are greatly increased, while those at the other corner are decreased. Therefore, there will be an increased loss in the coppor at one pole edge and a decreased loss at the other pole edge. However, as this loss at high inductions will vary almost as the square of the ampere-turns in the armature teeth, it is evident that the reduction in the loss at one pole corner may be small compared with the increase in loss in the copper at the other pole corner. The resultant loss can be calculated approximately by using the formula already given for no-load conditions, but with the ampere-turns in the teeth based on the load conditions. This would give a loss corresponding to no-load with the maximum induction in the teeth raised to peak value with load. This would include losses for the two pole corners; therefore, the result should be halved, as the peak density occurs at only one pole edge.

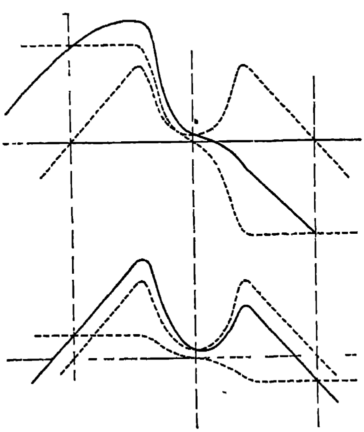


FIG. 6

If the empirical formula given for the copper loss represents the facts, even to a merely approximate degree, the results are very startling when applied to some of the old-time machines. The calculations show that in some cases the eddy current copper loss at heavy load was several times greater than at no-load. This should be true, but to a much less extent, in more modern types of machines. The results indicate that in many cases there will be considerable gain by reducing the field distortion through high saturation in the pole face, pole horns, etc. This saturation, however, would have to be

so arranged as to give the most beneficial field distribution with load, and haphazard methods of cutting off pole corners, without regard to the field form with load, would have to be avoided. In fact, in the past, the cutting away of pole corner laminations, in many cases, has been largely for the purpose of improving commutation, and not to obtain the best field form with load.

Pole Face Losses, with Load. The pole face losses will obviously be affected locally by change in the flux density in the air gap or at the pole face. Field distortion will tend to increase the loss at one pole corner and decrease it at the other. The increase will usually considerably exceed the decrease, but the resultant will not be increased in anything like the same proportions as the copper eddy current losses under the pole corners are increased with load. A rough approximation for the increased iron loss could be obtained by comparing the squares of the densities, at several points along the distorted field form, with the squares of the densities of the no-load field form corresponding to the total induction.

As the increase in pole face losses with load will, in some instances, be considerably less than the increase in the eddy current losses, it might be advantageous in such cases to decrease the field distortion by pole face saturation, even at the expense of increasing the no-load pole face losses. For example, if, in an extreme case, the air gap were decreased 20 per cent and the air gap ampere-turns thus gained were expended in suitably saturating the pole face material, then the full load field distortion might be much less than with the larger gap, with the same total field magnetomotive force. The no-load eddy current copper losses would be practically unchanged, while the no-load pole face loss would be increased. However, the full load pole face loss, due to the reduced distortion, might be no greater than with the larger gap, while the eddy current losses in the copper might be very much less than with the larger gap. In consequence, while the total no-load losses would be increased somewhat, the full load loss would be smaller than before, and the carrying capacity of the machine would be actually increased. This would apply, however, only to those machines where the no-load eddy current and armature tooth losses are relatively high and where the distortion is rather large with load.

Stray Losses. When the machine is carrying load, the stray

losses given under the no-load conditions may also exist and at the same time some of these may be greatly exaggerated. Also, other losses may appear which are not found at no-load.

Copper loss due to short-circuiting the armature coils in an active field will sometimes be more pronounced than at no-load, particularly in non-commutating-pole machines in which the brushes are shifted into an active field to produce commutation. This field, as a rule, will only be of proper value to produce proper commutation at some definite load, while at other loads there may be very considerable local currents in the short-circuited coils which may produce loss.

As the main field flux is crowded toward one pole corner and the field form becomes more pointed in shape, the effect of variable reluctance in the air gap may become more pronounced than at no-load, and, therefore, pulsations of the main field flux may cause more loss in the short-circuited armature coils.

Stray fluxes from the main poles will be distributed differently from the no-load condition and the densities of these stray fields may be considerably higher at certain points and thus give increased losses.

Additional losses at full load may be due to fluxes set up by the magnetomotive force of the armature winding itself when carrying load. For instance, the armature winding will set up magnetic fields, through the end windings, which fields are fixed in space, in a rotating armature machine. Bands or supporting parts, or other solid metal, rotating with the end winding, may cut these stationary fields or fluxes, and thus losses may be set up which are a function of the load.

Another source of loss at load may be found in the operation of commutation itself. A magnetic field or flux is set up by the armature winding across the slots from one commutation zone to the next. At the point of commutation this flux is reversed in direction with respect to the armature conductors, and, therefore, there will be local currents set up in the armature copper tself, due to this action. This, however, should be more properly charged to commutation loss rather than to armature core loss.

The above covers the principal core losses in direct-current machines. It was the original intention to analyze the core losses in the various types of rotating machines, but it soon developed that the subject was too extensive for the scope

of this paper, therefore it was limited to d-c. machines only. However, many of the conditions which hold for d-c. machines also apply, to a certain extent, to many other types. In addition there are losses in d-c. machines which are relatively large compared with those in other apparatus, due to the fact that the tooth saturation in d-c. machines is frequently carried much higher than in other apparatus.

The foregoing treatment of core losses is qualitative rather than quantitative, and it deals with the simpler phenomena only. It omits some very complex conditions, such as the effect of pulsations in flux superposed on high densities, displaced minor hysteresis loops, etc., which mean additional losses. The principal object of the paper is to give a better idea of the possibilities and impossibilities of the problem of core losses.

IRON COMMUTATORS

FOREWORD—During the past two years 1916-1918, frequent inquiries have been made as to why iron is not used instead of copper in the construction of commutators. Apparently it has been assumed, in some instances, that the present use of copper is more or less of a fad and that other metals, such as iron, could be used if desired.

This paper appeared in the Electric Journal, July, 1918. —(ED.)

IN the course of the development of commutating machinery various metals have been tried out in commutators, all the way from pure copper, both hard and soft, through various alloys and brasses, cast copper of various purities, aluminum, wrought iron, clear down to cast iron. All such materials have received consideration at some time or other and have been given fairly conclusive tests. Experience has shown that all of them could be used in commutators if one is willing to pay the price, this price being in the first cost of apparatus, in maintenance or in less satisfactory operating characteristics, or a combination of all. Under the stress of war conditions it may be necessary to pay any price, and apparently this is the condition which has confronted German manufacturers. In consequence, materials and constructions are used simply as a matter of necessity which, however, may not conform to conditions of even reasonably good design.

The use of copper in modern commutators is a matter of development and not simply a fad. In fact, most of the early commutating machines used other metals in their commutators, which would now be considered quite unsuitable. Cast copper and various brasses and bronzes were used quite extensively, with more or less bad results. Pure copper was considered too expensive for general use and it was only after very considerable development that the conclusion was reached that its apparent higher first cost was more than neutralized by improved maintenance and operation. Even after pure copper had come into general use for commutator construction, it was not known, or understood, why it was so superior to other metals.

About twenty-seven years ago the writer made extended tests on the use of iron in street railway commutators. The ma-

chines soon developed "high mica" and the commutators gradually blackened, the contact surfaces blistered and sparking gradually increased until the commutating conditions became practically impossible from the operating standpoint. These conditions repeated themselves in every test until finally this construction was given up as impracticable. The difficulty was blamed largely upon high mica, as it was assumed that, in some way, the metal wore below the mica, thus causing bad brush contacts, with resultant burning and blackening. It was not recognized that the converse was really the case and that the high mica was the result of burning rather than the cause. In all machines of those days there was more or less tendency for the commutators to "wear" considerably, and it was not recognized that such was not true mechanical wear, but that it was the result of burning away the contact surfaces.

A little later, the writer made quite complete tests on the use of aluminum on street railway motor commutators. This material worked better than iron, in the sense that burning and blackening and high mica did not appear as quickly as with the iron. However, like the iron commutator, there was no tendency to polish, but the commutator soon assumed a dull appearance which gradually changed to a blackened and burnt condition.

Bronzes and brasses were tried on similar railway commutators, and while these gave better results than the aluminum or iron, yet they developed high mica much more quickly than the copper commutators. With such evidence at hand, the use of forged or drawn copper for commutator bars was a natural conclusion. However, even with the best copper obtainable, there was some tendency toward blackening and burning of the commutators, generally accompanied by high mica, and the difficulty was blamed primarily on the mica. It was assumed that the copper bars did not wear as rapidly under the carbon brush as was the case with other metals. At the same time it was recognized that when the machine was operated without current none of these metals seemed to wear unduly. It was only when considerable current was carried that the wear was excessive. At that time, the real explanation of this difficulty was not fully appreciated.

Later investigations on collector rings and commutators, developed the fact that whenever a current is carried between a stationary brush contact and a moving surface, there is a tendency to burn away either the brush contact face or the moving surface,

depending upon the direction of the current and upon the current density. It was found that this burning action, which is somewhat similar to that occurring in an arc, was to some extent a function of the contact loss. This was indicated partly by the fact that the burning was a function of both the brush contact drop and the current density. A given current, for instance, might produce very little burning as long as the contact drop was quite low; whereas, if for any reason such contact drop increased materially, noticeable burning would begin. If the current was from the brush to the commutator or collector, the brush contact surface would tend to burn away more than the opposing surface. If, on the contrary, the current was from the collector or commutator to the brush, then the collector surfaces would tend to burn and, in some cases, deposit the burnt material on the brush face.

When carbon brushes are used, there is usually a very considerable contact drop due, apparently, to the nature of the materials in the brush itself. This drop, in many cases, is in the nature of one volt for each contact and it is fairly constant over quite a wide range of current. In consequence, the contact loss varies nearly in proportion to the current and not as the square of the current. Due to this very considerable loss with carbon brushes, there is a tendency to burn away the brush surface and to burn and blister the commutator or collector surfaces with which the brush is in contact. This tendency to burn is dependent upon the actual current density in the brush (including local or short-circuit currents), but the resultant burning is largely a function of the material in the commutator or collector face. As the brush cannot make perfect contact with the metallic surface to which it is opposed, there are minute arcs at the contact and these evidently burn away the surfaces. However, the real burning action is dependent upon the inability of the surface to conduct away heat rapidly, for if the heat developed in the surface film is not conducted away with sufficient rapidity, then such surface is liable to be blistered or burned locally, even though moving with respect to the brush. Such burning or blistering naturally roughens the contact surface and increases the contact drop and thus tends to increase the arcing and burning action. Thus, if there is any burning action it tends to grow worse, cumulatively. This burning away of the surface leaves the metal surface of the commutator slightly lower than the mica, unless the latter wears mechanically at the same rate that the commutator metal burns away. As this

is not usually the case, high mica soon develops, simply by the action of burning away of the metal. Thus high mica is a result of the trouble, rather than the cause. However, as even a very gradual burning away will eventually leave the mica above the surface, modern practice has tended toward undercutting of the mica, so that even with a slight burning tendency the brush still maintains contact with the metal, thus preventing accentuation of the trouble.

As mentioned before, this burning action is a function of the contact voltage, the current density, and the non-burning or non-blistering qualities of the metal constituting the commutator. It is in this latter feature that copper has proven so superior to other metals. Extended experience shows that the heat conducting qualities of pure copper are so good compared with most other metals or alloys that the burning or blistering action of the current under the brush is very small, except for high current densities. Anything which tends to decrease the heat conducting properties of the commutator metal, tends to increase burning action. This has been very clearly demonstrated in elaborate tests of carbon brushes on collector rings, etc., where questions of commutation did not come in to disturb the conclusions. Such tests have been made covering copper, bronzes and alloys of various sorts, wrought iron, cast iron, etc. In practically all cases, with high current densities, the burning and blistering action appears to be dependent upon the ability to conduct the heat away from the contact surface. By such conduction the local heating of the contact film of metal is kept at a low point which results in reduced fusion of the metal, and with very good heat conducting materials the fusion of the metal may be so minute that the polishing action of the brush keeps the surface in a smooth glossy condition.

It is an interesting fact that the electrical conductivities of the metals and their mixtures and alloys, bear a fairly close relation to their heat conductivities. Experience shows that very little impurity in copper will reduce its electrical conductivity to possibly one-third or one-quarter, and its heat conductivity will be decreased nearly in proportion. Most of the alloys of copper have a very low conductivity compared with copper itself, while wrought iron is worse than most of the copper alloys in this regard. The series of tests above referred to, indicated quite clearly that the burning tendency varied very much as the electrical resistance of the material, that is, with the heat resistance. Wrought iron, having

from eight to ten times the resistance of copper, would burn or blister and get rough at very much lower current densities than copper commutators or rings. Even some of the alloys which appeared to be good for collector rings, showed blistering effects at very much lower limiting current densities than copper. Consequently, it developed that the limiting carrying capacity of different metals in commutators and collector rings, varied roughly with the heat conducting qualities, and thus copper proved to be superior to any of its alloys or any other available material. According to this line of reasoning, silver should be better than copper, but this is not an available metal. The above also explains why alloys of copper in which other elements have been introduced for the purpose of hardening, etc., usually do not have the ultimate carrying capacity found in copper. Aluminum has fairly good heat conductivity, if pure, but it is so easily oxidized and the resistance of the oxidized surface rises so rapidly, that presumably this fact neutralizes any possible gain otherwise. Experience on actual commutators showed that aluminum did not take a polish, even under moderate current densities and, in fact, it acted very much like some of the higher resistance metals used in the tests.

It should be evident from the above that, when materials of higher heat resistance, that is, with poorer heat conductivity than copper, are used in commutators, the operating current densities should be reduced accordingly. Thus, it may be possible to use iron or steel for commutator bars, provided the brush current densities are reduced sufficiently. In very small machines, this might mean only an increase in the dimensions of the commutator and brushholders. In larger machines, however, any material modification in the proportion of the commutator may lead to radical changes in the machine as a whole, so that the total cost would be materially higher than in the copper commutator machine. This depends entirely upon how much sacrifice is to be made in operating conditions and maintenance. If these are to be kept at the same high standard as on present copper commutator machines, then it is questionable whether the iron commutator would prove to be practicable under any conditions. The same conditions hold true, to a certain extent, with certain alloys instead of copper in the commutator. As such alloys, as a rule, cost nearly as much as copper itself, it should be obvious that any material increase in the dimensions of a commutator will soon balance any possible gain.

In larger machines one serious condition would be liable to be encountered with other than copper commutators. At present these machines are built for quite high peripheral speeds of the commutators, and construction difficulties are encountered which would make any increase in their length or diameter very objectionable. Consequently, serious modifications in the general construction of the machine, and possibly in its speed conditions, are liable to be necessitated. In fact, in many cases the whole design of the machine is predicated on the commutator construction In such cases the use of a poorer material in the commutator would undoubtedly be a backward step in the development.

It is thus obvious, that the use of iron in commutators, while possibly practicable under the urge of necessity, is not in the direction of an advance in the art. In fact, it is a big step backward. It should be assumed naturally that if, in the past thirty years of development in commutating machinery, iron commutators have not come to the front, it is for very good reasons, and the preceding is simply an attempt to bring out some of the foremost reasons.

POLYPHASE INDUCTION MOTOR WITH SINGLE-PHASE SECONDARY

FOREWORD—Repeated requests had been made of the author, from time to time, for a simple explanation of the half speed characteristics of a polyphase induction motor with single-phase secondary circuit. The analysis presented here does not require more than a working knowledge of the characteristic principles and curves of the polyphase induction motor.

This appeared in the Electric Journal, September, 1915. —(Ed.)

IT is well known that when a polyphase induction motor is operated with only one secondary circuit closed—that is, with a single-phase group-wound secondary, it will develop at full speed a maximum torque much less than with polyphase secondary, and then with increasing load will drop to approximately half speed, where it will develop comparatively high maximum torque. However, a simple non-mathematical explanation of the causes of this action has not yet been put forward, to the writer's knowledge. Such an explanation is possible, and the following is one which should be grasped without difficulty by those who are familiar only with the general characteristic curves and actions of induction motors.

To begin with, consider the relations between the rotation of the magnetic field and the mechanical rotation of the rotor in the two cases of rotated and stationary primary windings—that is, with the primary winding (1) on the rotor, and (2)—on the stator. In the case of the primary winding on the rotor, let the direction of the magnetic field rotation be in the lefthand direction (counter-clockwise), as indicated in Fig. 1. This rotating field tends to pull the stator around in the same direction (left hand). As the stator core and winding cannot rotate, the rotor, due to the torque between the rotor and stator, turns in the opposite direction (right hand). When starting from rest, the stator or secondary has the same frequency as the primary; then as the rotor speeds up in the right-hand direction, the magnetic field set up by the primary winding rotates in the left-hand direction, and therefore its speed relative to the stator becomes less and less until synchronism is reached. Thus the secondary or stator frequency generated

by the rotating primary field decreases until synchronism is reached, which is the normal action of the polyphase rotor.

Considering next a stationary primary winding and a rotating secondary, and assuming right-hand rotation of the magnetic field, as shown in Fig. 2, it is obvious that the secondary winding and core will be pulled around in the same direction—that is, the rotor will turn in the right-hand direction. Thus, left-hand rotation of a primary magnetic field on the rotor, and right-hand rotation of a primary magnetic field on the stator, both tend to give right-hand rotation of the rotor. These two conditions are explained rather fully as they enter into the following explanation of the action of the induction motor with single-phase secondary.

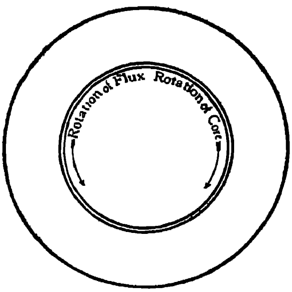


FIG. 1. PRIMARY ON ROTOR

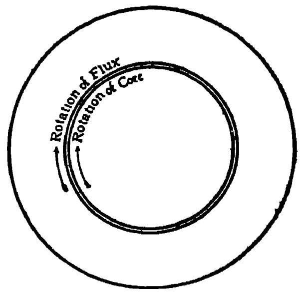


FIG. 2 PRIMARY ON STATOR

The next consideration is the resolution of a single-phase field in an induction motor into two components rotating in opposite directions at the same speed, each of half the maximum value of the single-phase field. Such component rotating fields, it may be asserted, do not actually exist, but, nevertheless, the resultant of two such fields of proper value and rotation will actually be a single-phase field corresponding to that set up by a single-phase winding on the motor. This assumption of two oppositely rotating fields as the equivalent of a single-phase field is a great aid in explaining the speed characteristics of the polyphase motor with single-phase secondary.

Assume next that the induction motor with single-phase secondary has its primary winding on the rotor and its secondary on the stator.* Consider first the standstill condition. The primary field is assumed to be rotating in the left-hand direction, as in Fig. 1. This field, cutting the secondary winding at synchronous speed, generates e. m. f. and current in the secondary, of

*This particular arrangement is chosen, as it appears to the writer to allow a somewhat clearer conception to be obtained of what takes place in the motor.

a frequency equal to the primary, but single-phase, due to there being but one closed circuit. This secondary current may be considered as setting up a single-phase field which is actually fixed in space, but which may be replaced by two oppositely rotating fields, each of half value, traveling around the core at a *speed synchronous with the frequency of the secondary current generated.* One of these rotating fields travels in the same direction and at the same speed as the primary field set up by the rotor windings. It thus corresponds to the rotating magnetic field set up by the usual polyphase secondary winding. The action between this rotating secondary field and the primary is that of a polyphase motor, and torque is developed at all speeds from standstill up to synchronous speed, as in the usual polyphase motor, as shown in Fig. 3. The rotor under the action of this torque tends to rotate in the right-hand direction.

Considering next the other component rotating field set up in the stator by the single-phase secondary current in the rotor, this rotates in the right-hand direction, or opposite to the primary rotating field. This secondary component field traveling around the stator may be considered as the primary field of an induction motor. For a secondary, it makes use of the windings on the rotor core, such secondary circuits being closed back through the primary transformers, supply system, etc. This may not be a very good secondary closed circuit, but it is all that is available and the motor does the best it can under the circumstances.

Let us now consider what torque conditions obtain with this right-hand rotating primary field with its freak secondary circuit. Taking standstill conditions first, it is obvious that as the primary field is on the stator and rotates right-handedly, the turning effort, or torque, will tend to run the rotor in the right-hand direction. Therefore, at start, the torque is in the same direction as in the case of the left-hand component. The two torques therefore add at start.

Considering next slow rotation of the rotor, as the primary winding on the rotor moves slowly in the right-hand direction the left-hand rotation of its flux decreases in speed with respect to the secondary winding, so that the secondary or stator frequency is correspondingly reduced. Therefore, the two oppositely rotating secondary component fields rotate more slowly. The left-hand one rotates at the same speed in space as the fundamental primary field, as described before. The right-hand component travels in

the opposite direction, while its secondary circuit, namely, the primary coils on the rotor, are rotating in the same direction (right hand), but at a somewhat lower speed. The torque exerted by this right-hand component is therefore still in the right-hand direction —that is, the same as that of the other component.

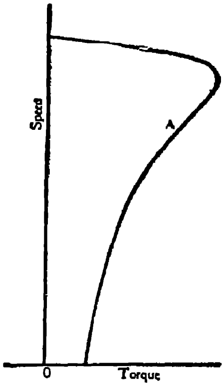


FIG 3

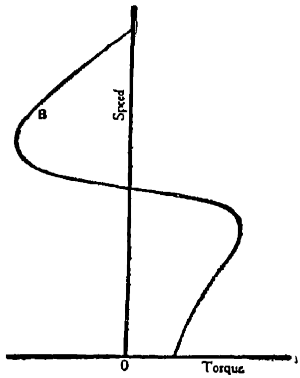


FIG. 4.

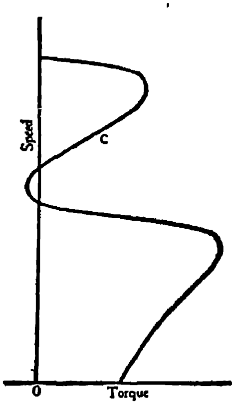


FIG .5.

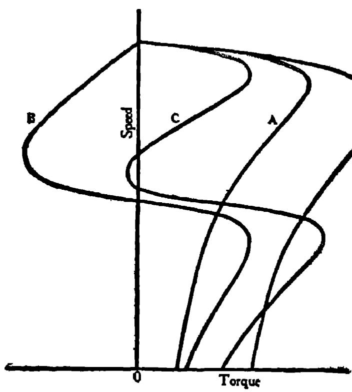


FIG. 6.

O—Torque of left-hand component, in synchronism with primary field and in the same direction. *B*—Torque of right-hand component, rotating in opposite direction and in synchronism with *A*, relative to the secondary winding *C*—Resultant of *A* and *B*. *D*—Torque of the same motor with polyphase secondary.

However, when half synchronous speed of the rotor is reached a new condition enters. At this speed the secondary frequency has fallen to one-half that of the primary or supply circuit. The

left-hand component of the secondary field is now traveling in the left-hand direction at half the speed it had when the rotor was stationary, but the primary field is also traveling left-handedly at the same speed in space, so that the two fields are still in synchronism.

Considering next the right-hand component, this is traveling at half speed in the right-hand direction, while the rotor is traveling at the same speed in the same direction. Therefore, the secondary circuit for this right-hand field (the winding on the rotor) is now traveling in synchronism with it, and therefore no secondary current or torque can be generated. This, therefore, corresponds to full speed on the usual induction motor. The torque-speed curve up to half speed, therefore, may be indicated by the lower half of the curve shown in Fig. 4. At higher than half speed the stator frequency is still further reduced and the right-hand field travels at a still slower speed, while its secondary winding on the rotor core is now traveling faster than its primary field, or it is running above synchronism. It therefore develops a negative torque. This negative torque above half speed should show a negative characteristic somewhat similar to the positive speed-torque curve below half speed. This is indicated in Fig. 4. However, there is this difference; as the rotor speed approaches true synchronism, the frequency of the stator circuit approaches zero, until at full speed of the rotor (synchronous speed) the secondary frequency becomes zero. Under this condition the stator field and currents fall to zero, and there is no torque from either the right or the left-hand component field. Therefore, as this zero frequency is closely approached, both torque curves rapidly approach the zero value. By combining the speed-torque curves for both component fields the resultant speed-torque curve may be plotted as in Fig. 5. It will be seen from this resultant curve that stable torque conditions are found at about half speed. Also, the starting torque is good. Above half speed the torque conditions are somewhat indefinite, depending upon individual circuit conditions, etc. In general, the rotor will continue to run at full speed, if first brought up to this speed by means of polyphase secondary operation, and will pull considerable load without dropping to the lower stable speed.

While the torque at start, due to the resultant of the two torque curves shown in Fig. 5, is larger than that due to the left-hand component alone, yet it must be borne in mind that this

latter may be much smaller than the starting torque of the motor with polyphase secondary. Therefore, this method of starting with one secondary circuit only is not, in general, an improvement on starting with a polyphase secondary. To illustrate this, another speed-torque curve should be added, representing, in a general way, the conditions with the same motor if a symmetrical polyphase secondary winding is used. This is shown in Fig. 6.* In general, this will show better starting and also higher maximum or pullout torque than with single-phase secondary.

To the experienced designer it will be obvious that such a motor is but one form of internal cascade, and a very poor one at that. A motor under such conditions of operation carries excessive currents, the primary winding carrying both primary and secondary currents, these being of different frequencies, except at standstill. The power-factor is also comparatively poor.

---

*The curves *C* and *D* in Fig. 6 have been plotted partly from actual test data.

A PHYSICAL CONCEPTION OF THE OPERATION OF THE SINGLE-PHASE INDUCTION MOTOR

FOREWORD—In the training of young engineers, directly from the technical schools, the author has found that very few of them have any conception of the operation of the single-phase induction motor. In attempting to work out a simple method of presenting the problem, the subject matter of this paper was gotten together from time to time, and eventually it was written in its present form and presented before the American Institute of Electrical Engineers in April, 1918. It should be understood that the purport of this whole paper is to illustrate the principles of operation and not to indicate a method of calculation. The usual methods of treating the single-phase induction problem are so mathematical that the average engineer or student cannot follow them. In the method given in this paper a knowledge of the characteristics of the polyphase motor is necessary, as the entire method is based upon the fundamental idea of a pair of polyphase machines operating with variable voltages and opposing torques. From this viewpoint, the various characteristics of the single-phase motor are explained in a non-mathematical manner.

It may be considered, to a certain extent, as supplementary to the author's paper on "The Polyphase Motor," which was published twenty-one years before, and which is reprinted in the first part of this volume.—(ED.)

THE underlying principles and the operating characteristics of the polyphase induction motor are so well understood that it is found desirable to consider the single-phase induction motor, simply as a special case of the polyphase. The following treatment of the subject should not be considered as an analysis of the true phenomena of the motor but should be looked upon more as a ready means of visualizing the actions in the form of well known polyphase motor characteristics. Also, it should not be considered as a presentation of new material, for the underlying methods used are old and relatively well known. It is simply an attempt to describe the operation of the single-phase motor in a way which may be most easily understood by those not versed in the mathematics of the subject.

Starting with the old assumption that a single-phase alternating magnetic field may be considered as being made up of two constant fields, each of half the peak value of the single-phase field and rotating at uniform speed in opposite directions, then

if the single-phase flux distribution is of sine shape and varies sinusoidally in value, it may be replaced, or represented, by two sine-shaped fields of constant value rotating in opposite directions. This is the simplest case and allows a relatively easy explanation of many single-phase problems. However, when the flux distribution, or field form, due to the single-phase winding, is other than of sine shape, then the oppositely rotating components cannot be considered as of sine shape, but will assume certain varying forms as they rotate, the resultant of each instantaneous pair always giving the single-phase field corresponding to that instant.

As other than sine-shape fields tend toward complications in the physical conception of the single-phase induction motor actions, and lead more or less into the mathematical conception, the following analysis will be limited essentially to sine-shape distributions.

As a starting point and to show reasons for certain later analysis, let us assume a single-phase induction motor operating at no-load, full speed, with its polyphase secondary winding short-circuited. The single-phase primary field, of assumed sine shape, is considered as made up of the two sine-shape equal components of constant value, and of half the peak value of the single-phase field, and rotating synchronously in opposite directions. One of these fields is traveling in the same direction as, and slightly faster than, the rotating secondary. The slip of the secondary with respect to this field is of the same nature as in the ordinary polyphase motor. As the machine is carrying no load the secondary current corresponding to this rotating field is very small, being just large enough to overcome the rotational losses in the motor itself, and its frequency is equal to the slip frequency due to the forward field component.

As there is an assumed backward flux or field component of equal value, the rotating secondary winding cuts this at almost double the frequency of the line. Stated exactly, the sum of the backward and the forward frequencies, in the secondary winding, is equal to exactly double the frequency of the primary supply system. The secondary winding cutting the backward field at this high frequency tends to generate a very considerable e. m. f. and, with the winding closed on itself, short-circuit currents will flow, which tend to damp out or suppress the flux which causes them. This secondary current will rise until its magnetizing effect is practically equal and opposite to the magnetomotive

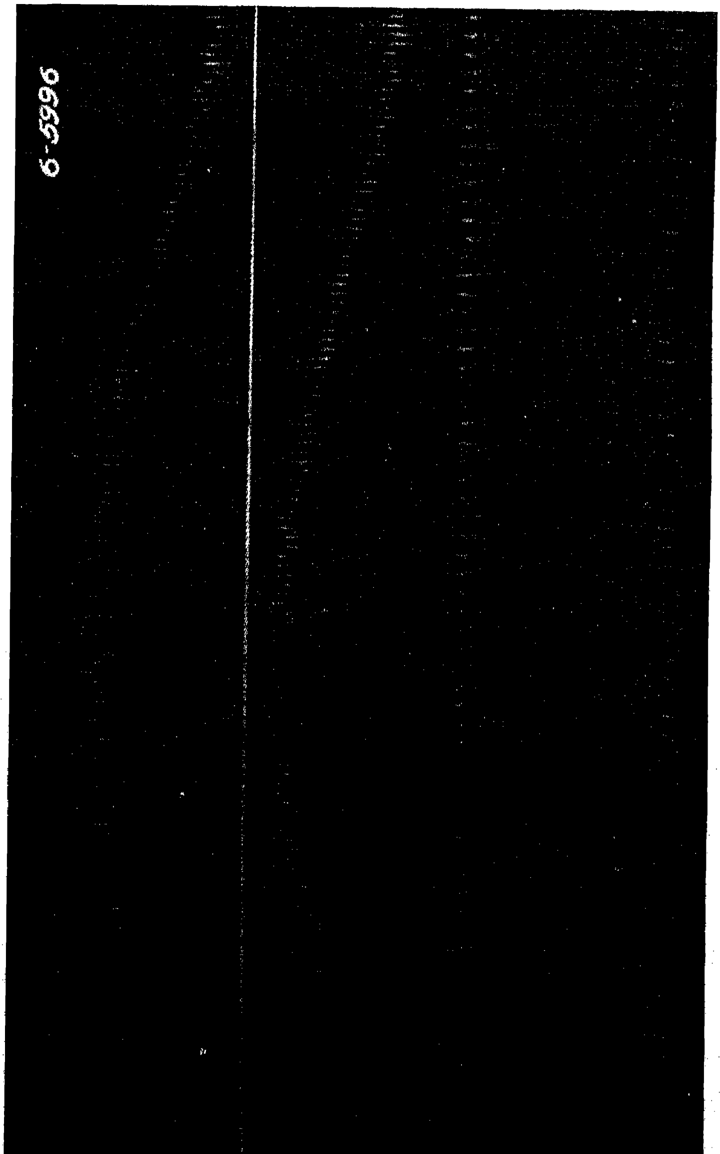


FIG. 1.

force which produces the backward field, which thus becomes almost zero in value. Consequently there are two distinct sets of secondary currents flowing, one of very small value and of a frequency corresponding to that of the forward rotation, and the other of very much larger value and of almost double the line frequency. Actual tests of the secondary circuit of a single-phase induction motor at small load, taken with an oscillograph, Fig. 1, show both of these currents as above described.

Magnetomotive Forces and Magnetic Fluxes

It is seen from the preceding that, right at the beginning of our analysis, a new condition is encountered, namely, the introduction of a secondary opposing magnetomotive force which reacts on one of the primary field components and practically neutralizes it. Also, there is a mixture of magnetomotive forces and magnetic fields, which is liable to lead to confusion. Obviously the introduction of the opposing secondary magnetomotive force rotating synchronously with the backward component of the primary introduces some entirely new features. Therefore, before going any further with the above method, it is desirable to set aside for awhile the viewpoint of two equal oppositely rotating fields and begin with a preliminary study of the magnetomotive forces and the magnetic fields resulting from them.

It may be mentioned that while the assumption of two oppositely rotating component fields, in place of a single-phase field, is well known and has been used quite frequently, the corresponding analysis, from the viewpoint of magnetomotive forces, apparently has been but little used. When magnetomotive forces, instead of magnetic fluxes, are considered, then the single-phase primary magnetomotive force, fixed in position, can be replaced by two equal components of constant value, such as would be developed by direct current, each of half the peak value of the single-phase, and rotating at synchronous speeds in opposite directions.

Returning again to our analysis, let us consider two fundamental magnetomotive forces, namely, a primary single-phase one, fixed in position and varying sinusoidally and a secondary one of constant value, of half the peak value of the primary which rotates synchronously in one direction and which is in opposition to the primary in the position where the two coincide.

Let us assume that the primary single-phase magnetomotive force is split into its two equal oppositely rotating components,

then the results may be illustrated as in Figs. 2, 3, 4, and 5. In Fig. 2, C and D represent the two components forming the single-phase magnetomotive force A. At the position chosen, C and D are of equal value and coincide in position and polarity, B, which represents the secondary magnetomotive force, is also of half the peak value of A, but is of opposite polarity. It, therefore, neutralizes one of the components C or D, thus leaving a resultant of half the peak value of A.

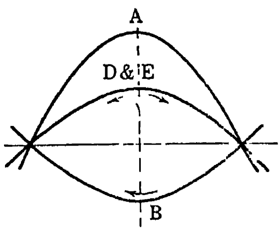


FIG. 2

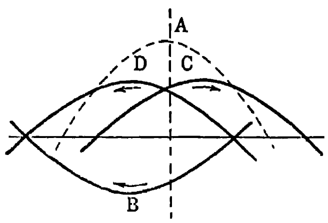


FIG. 3

In Fig. 3, the component D has shifted thirty degrees to the left, while C has shifted an equal distance to the right. The secondary magnetomotive force B is shifted thirty degrees to the left, thus neutralizing D and leaving only the component C.

In Fig 4, D and B are shifted sixty degrees to the left, while C is shifted sixty degrees to the right In the same way, in Fig. 5, B and D have shifted ninety degrees to the left and C has shifted a corresponding amount to the right.

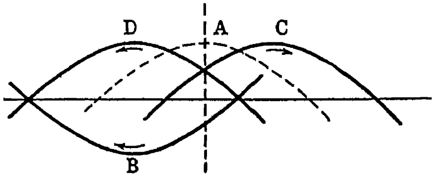


FIG. 4

Thus from the above it is seen that a single-phase magnetomotive force, fixed in position and varying sinusoidally, and a constant magnetomotive force of half the peak value of the single-phase, which is in opposition at the point of coincidence of position, and which rotates synchronously in either direction, will give a resultant constant magnetomotive force, rotating in the opposite direction, but which is of the same polarity as the single-phase magnetomotive force at the position of coincidence.

In other words, a single-phase magnetomotive force, fixed in position, and an opposing constant one of half the peak value rotating in either direction, will give a resultant rotating magnetomotive force equivalent to that of a polyphase induction motor.

As a continuation of the above, the resultant magnetomotive force *C* could be replaced by a magnetic field or flux, resulting from such magnetomotive force. If this magnetic field is plotted to the same scale as the magnetomotive force which produces it, then *C*, in Figs. 2 to 5, can represent a magnetic field. This field will be constant in value and of half the peak value of the field which the single-phase magnetomotive force alone would set up.

Thus according to Figs. 2, 3, 4 and 5, by the introduction of an "opposing" magnetomotive force, equal in value to one of the component magnetomotive forces of the single-phase and rotating synchronously with it, one of the two components of the magnetic field can be suppressed and only the other component left,

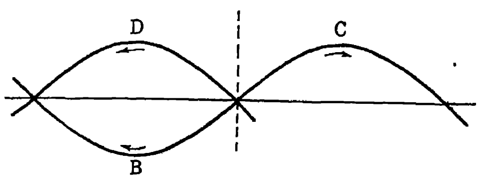


FIG. 5

the resultant is thus a rotating magnetic field, just as in the polyphase induction motor.

However, a further modification of this should be considered. Assuming again, that the single-phase primary magnetomotive force is replaced by its two equal rotating components, as in Figs. 2 to 5, then by the addition of an opposing magnetomotive force, similar to *B* in the same figures, but of *less value than the component D*, then the resultant of this opposing magnetomotive force and the component *D* is a reduced magnetomotive force of the same polarity as *D*. There will then remain two magnetomotive forces, each of constant value, one of half the peak value of *A* and the other of some smaller value, depending upon the opposing force *B*. These two rotating magnetomotive forces can, therefore, set up two oppositely rotating fields of *unequal* value. These are illustrated in Figs. 6, 7 and 8.

In Fig. 6, *B* is assumed at some less value than the component *D*. The resultant of *D* and *B* is shown as *E*. Therefore, at this

position C and E represent the two resultant magnetomotive forces and the two component fields. In Fig. 7, the conditions are shown for thirty degrees shift and here again E and C represent the two fields. In Fig. 8 the shift is for sixty degrees.

Thus by the introduction of a constant "opposing" magnetomotive force of less than either of the components of the single phase, two oppositely rotating fields of unequal value may be set up. As extreme cases of this, if the constant opposing magnetomotive force is made zero in value, the magnetic field corresponding to its position and rotation will rise to the full value of the oppositely rotating field; and, on the other hand, if the constant opposing magnetomotive force is made half the peak value of the single phase, the correspondingly rotating field becomes zero. Both of these cases are in accordance with the earlier assumptions

The above conditions of the single-phase primary magneto-

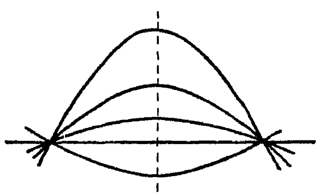


FIG. 6

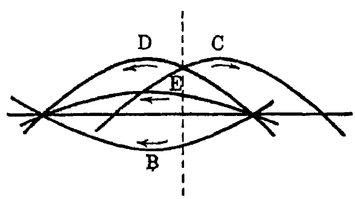


FIG. 7

motive force and a constant secondary one, in opposition, which may be of half the peak value, or some less value down to zero, and which rotates synchronously in one direction, resulting in two magnetic fields which may be of equal or unequal value, and which rotate synchronously in opposite directions, all form essential parts in the physical conception or visualization of the actions of the single-phase motor which will be given below.

It should be observed that in the above method of considering the production of a rotating field in the single phase induction motor, the two primary components of the single-phase magnetomotive force and the secondary damping magnetomotive force *all rotate synchronously,* and such rotation is independent of the speed of the secondary core. In some methods of considering the single-phase induction motor problem, the single-phase primary winding is assumed to generate a magnetomotive force in the secondary which, by rotation of the core, is carried around until it generates a second magnetic field or flux at right angles to the

original primary flux, thus giving the equivalent of a polyphase magnetic field. However, the above method does not involve such method of treatment.

It should also be recognized that the foregoing analysis only covers no-load conditions and that with the addition of load new conditions are brought in to the problem. These, however, will be brought out later, for the no-load conditions require further consideration, especially as regards the generation of the primary counter e. m. f. by the above described rotating fields. As already shown, there may be a single magnetic field rotating synchronously, or there may be two component fields of equal value rotating in opposite directions, or there may be intermediate conditions of oppositely rotating fields of unequal value, depending upon the value of the damping or opposing secondary magnetomotive force.

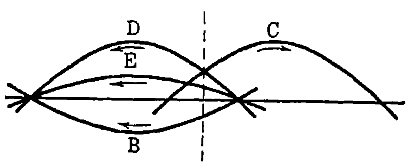


FIG. 8

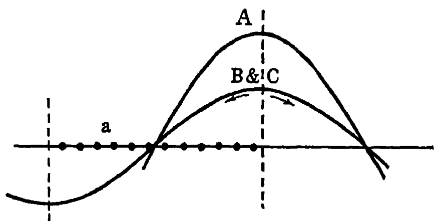
COUNTER E. M. F. GENERATION AND EXCITATION

Considering next the counter e. m. f. generated in the primary, we should first look into the e. m. f. conditions produced by two oppositely rotating fields of equal values. If the secondary circuits are open, the two component fields are both present and are concerned in the generation of the counter e. m. f. This is true whether the secondary is stationary or is rotated at full speed. If, however, the secondary is closed upon itself, then when running at speed, one of the component fields is practically damped out and the other must generate the entire primary counter e. m. f. Thus, two entirely different conditions are encountered, depending upon whether the secondary is open or closed. To explain this properly, some further analysis is required, as follows:

In the first place, it may be stated that the e. m. f., produced in the primary winding by *cutting* its two component fields, is the same as that generated by the single phase sine shape field, varying sinusoidally and acting on the primary winding as in a

transformer. Herein lies a simple illustration of the equivalence of the transformer and the flux cutting methods for calculating e. m. fs. In Figs. 9, 10 and 11, are shown several positions of the two oppositely rotating fields and their relation to the primary winding.

In Fig. 9 is shown the magnetic flux, or field, A, which is set up by a primary winding a. This winding, of course, would



FIF. 9

require a tapered distribution to give such a field. This is mentioned incidentally as it has no direct bearing upon the explanation, except from the mathematical standpoint.

Assuming the single-phase field at its maximum or peak value, then, at this instant, the two component fields, B and C, each of half the peak value, will coincide both in position and polarity. From the transformer method of calculation, the e. m. f. gener-

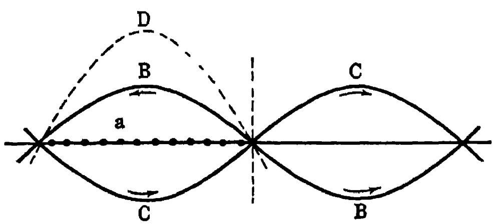


FIG. 10

ated at this instant, in the winding, will be zero, as the rate of change of the flux is zero. Also from the flux cutting method, the e. m. f. in the primary winding will be zero, for, as is evident from the figure, each belt or group of the primary winding is cutting fields which have equal positive and negative areas or values.

Considering next the conditions in Fig. 10, in which the two rotating components have traveled ninety degrees. The fields

are shown as B and C It is evident that the resultant of these two fields is zero in value, that is, the single-phase field is passing through its zero value, and, accordingly, is generating the maximum e m f. by the transformer method Also, considering component B of the rotating fields, obviously, by the cutting method it is generating maximum e m. f in the winding a Also, component C is generating maximum e m f in winding a However, as one of these fields is positive in this position and is traveling in one direction, while the other field is negative and is rotating in the opposite direction, the two e m fs will be in the same direction, and thus will be added. Thus, from the figure, this position will give the maximum e. m f. in the winding by the cutting method It can be shown by calculation that this maximum value is the same with either the cutting or the transformer methods of considering e m. f generation.

This shows that both of the component fluxes must be taken

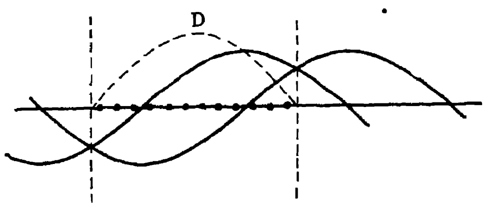


FIG. 11

into account in generating the total primary e. m. f , and if either component is decreased in value or suppressed, the total e m f. generated in the winding will be decreased correspondingly, unless the other component is increased a corresponding amount.

Fig 11 is simply a continuation of the conditions of Figs 9 and 10, in showing an intermediate position of the component field. The result is the same as if the two fields were momentarily replaced by the field D

According to the above analysis, to produce a given counter e. m. f. in the primary, with one of the component fields damped out, the other component must be doubled in value It was shown before that in the single phase induction motor, running at full speed with no load, the backward field is practically damped out by the secondary current. Thus with only the forward component field remaining, either the counter e m f. will be halved or the forward flux component must be doubled, the latter being the case This means, in turn, that the primary

magnetomotive force must be doubled in value. In other words, suppressing one of the two rotating field components results in doubling the no-load excitation of the motor. Furthermore, doubling the magnetomotive force of the primary and thus doubling the forward component of the field also doubles the backward component, which, in turn, is suppressed by doubled secondary current. The above conditions of doubled excitation is on the basis of sine flux distribution. With other distributions the same result holds approximately, but not exactly, due to conditions involving the shape of the field.

It is evident from the above that, with the secondary circuits open, the excitation required is of constant value regardless of the speed of the rotor core and windings; also when running at speed, the primary excitation is doubled as soon as the secondary circuit is closed. However, it is not obvious, on first consideration, that even with the secondary circuits closed the primary excitation falls to half the full speed value, when the motor is brought to standstill. This involves load conditions which will be treated later, but nevertheless this feature may be brought out at this time. The explanation lies in the fact that at rotor standstill the damping action of the secondary current will be exerted equally on both the forward and backward components of the primary field, so that necessarily these must be maintained at equal value, and, by the above analysis, this requires but half the excitation, compared with the no-load full-speed condition where the backward field is practically completely suppressed.

Load Conditions

When the single-phase induction motor is loaded, the total input current can be considered as made up of two components, namely, the no-load (practically all magnetizing) and the load current. This latter is simply the increased current in the primary due to the load and does not entirely represent energy. This load current, being single-phase, may be represented by two equal oppositely rotating magnetomotive forces in the primary of the motor, just as in the case of the no-load current. The fields which these two magnetomotive forces tend to set up are both practically suppressed by two equivalent *secondary* magnetomotive forces rotating in opposite directions. The forward secondary component corresponds to the secondary load magnetomotive force in the polyphase motor and the interaction between this magnetomotive force and the forward primary field

develops torque just as in the polyphase motor. The backward component, at first thought, would appear to develop an opposing torque, corresponding in value to that of the polyphase motor at approximately 200 per cent slip. This, however, is not the case, for at this slip the ordinary polyphase motor takes an excessive primary current tending to develop a large magnetic field, which is suppressed by a correspondingly large secondary magnetomotive force. In the single-phase induction motor, however, the primary backward rotating magnetomotive force component, due to the load current, can be only of the same value as the forward. This fact must be borne in mind as it is a very important factor in the later analysis.

To illustrate the characteristics of the single-phase induction

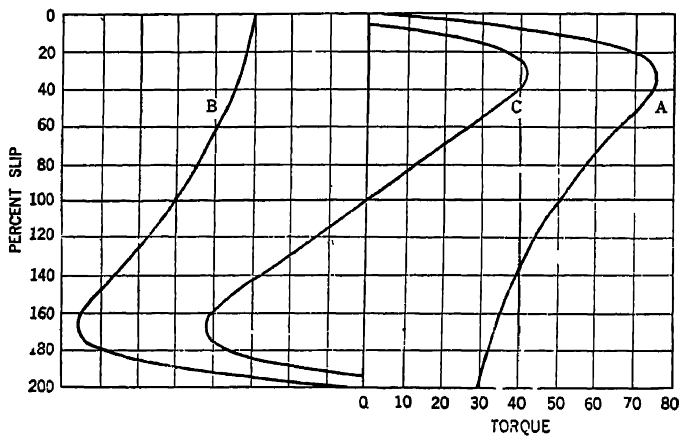


FIG. 12

motor, it may be compared with the action of two polyphase induction motors rigidly coupled together, and connected to the line to give opposite rotations. Such a set or unit has certain characteristics which are so similar to those of the usual single-phase induction motor that on first consideration one would assume them to be identical. However, a more careful study of the individual operating conditions shows that the similarity is only a general one, and a number of decided discrepancies are found.

The characteristics of the above two-motor unit and the single-phase motor may be compared as follows:

(1) The speed torque characteristics of the two motors of the polyphase unit may be represented by *A* and *B* in Fig. 12 and

their resultant by curve *C*. According to this latter curve, the resultant torque is zero at standstill, and a slight change in speed in either direction will give an effective torque tending to speed up the unit in whichever way it is started. This, therefore, corresponds to the well known starting characteristics of the single-phase motor.

(2) It may also be seen that the maximum torque the unit develops is materially less than that of either of the two component motors This fact is also consistent with single-phase motor operation compared with the same machine on polyphase.

(3) At full speed, according to this resultant curve, the slip

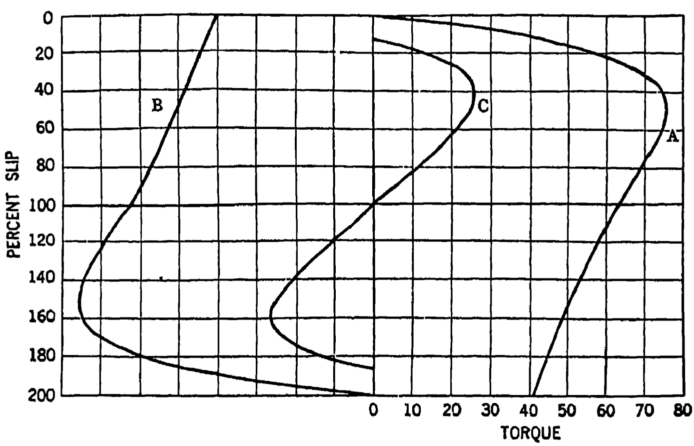


FIG. 13

for a given torque is very much larger than that of the corresponding polyphase motor. This is not true of the single-phase motor and herein lies one of the discrepancies in this method of illustrating the operation.

(4) It is well known that in the polyphase motor the maximum torque it can develop, with constant voltage applied, is independent of the secondary resistance; while, in the single-phase motor, in general, an increase in the secondary resistance will decrease the maximum torque and a decrease will have the opposite effect. This may be illustrated by repeating the curves of Fig. 12 with modified secondary resistance in the two component motors. In Fig. 13 the secondary resistance is increased and in Fig. 14 is decreased relatively to that of Fig. 12. The

resultant speed-torque curves for the three figures show that the maximum torques are materially affected by the secondary resistance. The same holds true for the single-phase induction motor.

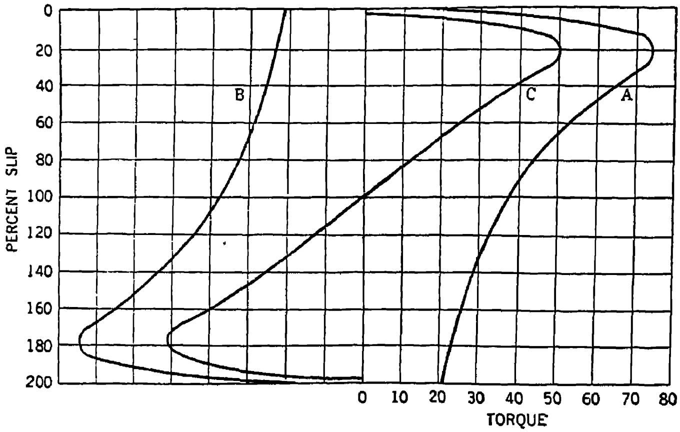


FIG. 14

(5) However, this method of illustrating the characteristics of the single-phase motor torque fails when the conditions of secondary resistance is such that the maximum polyphase torque

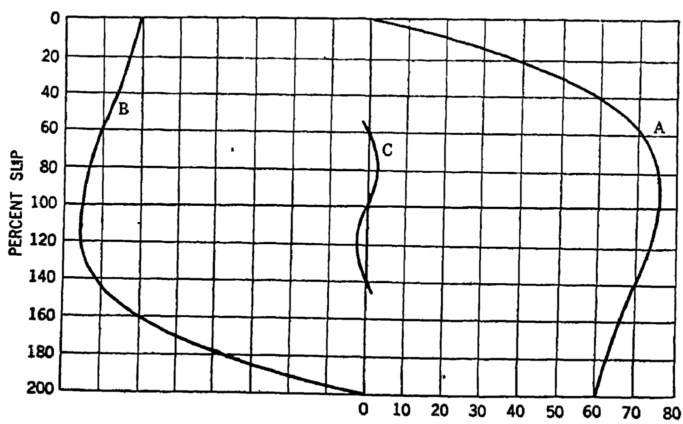


FIG. 15

is developed at about 100 per cent slip. Fig. 15 illustrates this. From this speed torque curve it appears that the unit has a very low resultant torque, but this is not the case in the single-phase

induction motor, for with a polyphase motor developing its maximum torque at 100 per cent slip, the same machine on single-phase will give a very considerable maximum torque. Here again is a discrepancy which the assumed equivalent arrangement does not cover properly.

(6) In Fig 16, the current-torque curve D, for the component motors in the above figures, is shown. This indicates plainly what a wide discrepancy there is between the currents taken by the primaries of the two motors when running at speed. For example, at a given speed a, the current taken by the forward rotating motor is b, while c represents the current taken by the backward motor. Obviously, the current taken from the line, which is the resultant of b and c, is much greater than that required to produce the resultant torque and the power factor of such a unit must necessarily be very poor. However, such is not the case with the single-phase motor, for the inputs and the power factors are not greatly different from those of polyphase motors of the same capacity. Herein lies a radical difference between the single-phase motor and the above assumed unit.

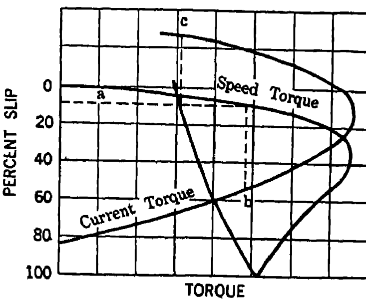


FIG. 16

(7) Another difference between such a unit and the true single-phase motor lies in the no-load or magnetizing input. Obviously, the combined magnetizing components for the two motors will be twice as great as for a single machine, whereas, in the single-phase motor the magnetizing input is practically the same as in the corresponding polyphase machine. Here is another pronounced discrepancy.

It is evident from the above that while this method of illustrating the action of the single-phase motor by means of two polyphase motors, coupled for opposite rotation, is in the right direction, some special modifying conditions must be introduced to account for the discrepancies. The action of this two-motor unit, therefore, will be followed up further, with the introduction of certain modifications derived primarily from consideration of certain characteristics of the single-phase induction motor itself

In the first place, curves A, B and C of Fig. 12 were based upon equal and constant e. m fs. applied to the terminals of both

motors. That this is not a correct assumption can be determined from the operating conditions in the single-phase motor. From the analysis of the component rotating fields it was shown that at full speed the backward component was practically damped out by a secondary magnetomotive force, thus leaving only the forward component, which then rose to practically double value in order to generate the required e. m. f. However, at standstill, the secondary winding holds the same rotational relation with respect to both component fields and, therefore, neither field can be damped out more than the other. Consequently, at standstill, both component fields are equal in value and the counter e. m. f. of the primary is generated by the two oppositely rotating fields, instead of a single one of double value

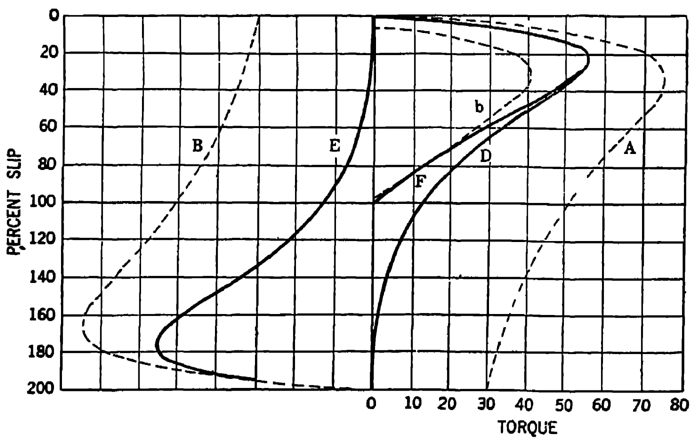


FIG. 17

as is the case at full speed. Therefore, at standstill, the forward field is of only half the value of the full speed field. This corresponds to the operation of the polyphase motor at half field strength, that is, *with half the primary voltage applied,* thus requiring one-quarter the magnetizing input. The same voltage condition applies also for the backward component at zero speed.

It would appear, therefore, that in the unit composed of two polyphase motors coupled together, the voltage applied to the terminals of the forward motor should be at practically full value at synchronous speed and should fall to half value at standstill or 100 per cent slip, and should have practically zero value at 200 per cent slip. Then assuming, as a first approximation, that the decrease in voltage from full speed to 200 per cent slip

is a straight line law, new speed torque curves, corresponding to Fig. 13, but with the torques decreasing as the square of the voltage, can be illustrated as in Fig. 17. Here curves A and B correspond to Fig. 12, while D and E correspond to the above proportionate reductions in voltage. The resultant F of these latter curves is also shown.

This new resultant F is similar in general shape to C of Fig. 12, but indicates some quite different characteristics. For instance, at the higher speed values it coincides quite closely with the polyphase speed torque curve, which is actually the case in the single-phase motor. In the second place, with high secondary resistance, as shown in Fig. 15, the speed-torque curves are modified as in Fig. 18, which shows both the former characteristic

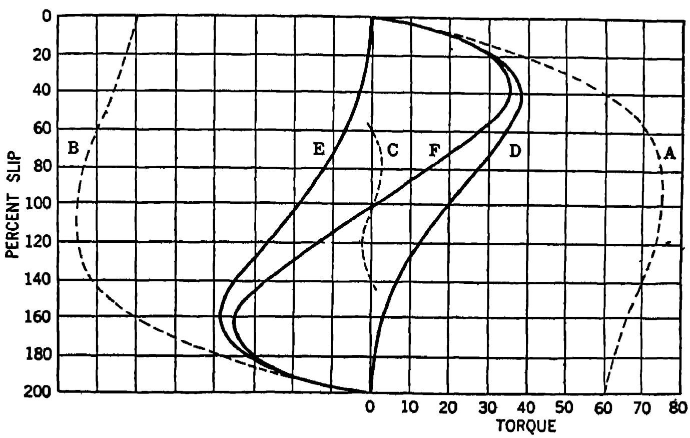


FIG. 18

and the new one. Here the resultant torque, under the new assumption is materially higher and more nearly conforms with the condition in the single-phase motor.

Under the earlier assumption of constant voltage on both motors, it was shown that the magnetizing current would be twice as great as in the single-phase motor. On this new assumption, however, at full speed, with practically full voltage on one motor and zero voltage on the other, the total magnetizing current will be only half as great, and will approximate that of one motor alone, and, therefore, that of the single-phase motor.

Furthermore, under the new assumption, the current taken by the primary of the backwardly rotating motor is quite small at high speed and, therefore, the resultant current taken from the

line is not excessive and is more nearly consistent with actual single-phase motor conditions.

Thus, with this new condition of reduced terminal voltage with reduction in speed, practically all the conditions of the single-phase motor are met, except possibly from the quantitative viewpoint. The two-motor combination thus serves as a very good illustration. There is, however, one further condition *which must be rigidly met* if the new curves are to be reasonably exact, namely, *the primary currents taken by the two motors must be equal,* for, as shown in the early part of this analysis, the forward and backward rotating components of the primary current in the single-phase induction motor are equal at all times. Consequently to duplicate this condition, the primary e. m. fs. im-

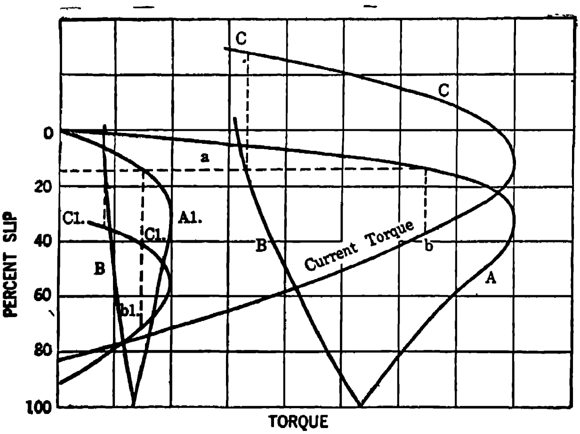


FIG. 19

pressed upon the terminals of the two polyphase motors should be varied in such a way that the primary currents will always be equal. In addition, it is assumed that the sum of the two impressed voltages is constant. This, however, is only an approximation.

The next step is to determine what is the actual law of voltage variation which will satisfy the above conditions of current and voltage. A ready means for obtaining this lies in the speed-torque and current-torque curves of the polyphase motor at constant voltage. From the current-torque curve at constant voltage corresponding curves for any other voltage can readily be plotted by varying the abscissae as the square of the voltage and the ordinates directly as the voltage. This is illustrated in Fig. 19. Here A is the polyphase motor speed-torque curve at

constant voltage B represents the part below the 100 per cent slip line, but turned above the zero speed line for convenience. B can also be considered as the back torque at full voltage, but thrown to the right of the zero torque line for convenience. Curve C represents the primary current for full voltage conditions Then at a speed a, for example, the primary currents corresponding to the forward and back torque will be b and c respectively.

Assume next that the voltage is halved for both rotations, then the new speed-torque curves will be A_1 and B_1 in which the torques are reduced as the square of the voltage. The new current curve will be C_1. The currents for speed a will now be b_1 and c_1, or half of b and c, as they are varied as the voltage.

The above figure is simply to illustrate the rule for variation of the primary current with the voltage, in the polyphase motor, and does not represent the actual conditions which we are after; for in the above the voltage reductions are the same for both the forward and the back torques. But, according to our former analysis, this condition of equal voltages, for the two rotations, holds only for the 100 per cent slip point. For other speeds the two voltages are reduced unequally, but with the sum of the two approximately constant according to the assumptions.

If, for any speed a, we let x represent the percentage of voltage reduction for the forward torque, then $1 - x$ will represent the corresponding reduction for the back torque. Let I_f be the primary current, corresponding to the forward torque for this speed at full voltage, and I_b the current for the back torque at the same speed and also for full voltage. Then $I_f x$ will represent the primary current at the reduced voltage for the forward rotation and $I_b (1 - x)$ will be the primary current for the back rotation. One of the conditions of our two-motor unit, to make it correspond with the single-phase motor, is that these two primary currents must be equal. Therefore, $I_f x = I_b (1 - x)$, and

$$x = \frac{I_b}{I_f + I_b} \text{ and } (1 - x) = \frac{I_f}{I_f + I_b}.$$

The above allows the determination of the percentage x of full voltage which must apply for each speed between zero and synchronism, when the values of the current I_f and I_b for full voltage are known.

A second method of determining the percentages of voltage

for the two rotations is available when the speed-torque curve of the motor on single phase has been determined, by test or otherwise. By our former assumption this single-phase torque is the difference between the speed torque curves for the forward and backward rotations with the respective voltages reduced the proper percentages. These torques for any given speed vary as the square of the terminal voltage. For example, calling T_f the forward torque, at full voltage and speed a, and T_b the back torque, and T_1 the single phase torque for the same voltage and speed, then $T_f x^2 - T_b (1 - x)^2 = T_1$, from which x may be determined, with T_f, T_b and T_1 known.

It would appear from the preceding that, if the assumptions made are anyways close to the actual conditions, this method of analysis shows a means for deriving the single-phase speed-torque curve from the polyphase curves of the same machine. Methods of calculating the primary current and speed-torque characteristics of the polyphase motor have been developed quite completely, so that it is not necessary at this place to give any details of such methods. The accuracy of the methods for calculating the polyphase curves depends almost entirely upon the correct determination of the reactance and saturation constants. All methods for the direct determination of the single-phase speed-torque characteristics also involve the use of corresponding reactance and saturation constants. Therefore, the above method brings in no new and more difficult conditions. The primary object of this paper, however, is not to develop a new method of calculation, but simply to give a better conception of the close relation of the single-phase and polyphase characteristics.

After development of the above method, an attempt was made to check it by applying certain existing test data, but without positive results, although the indications were quite satisfactory. It was discovered that in all the existing test data at the writer's command, where the polyphase speed-torque and current-torque curves has been obtain by actual test, constancy of temperature had been more or less disregarded. The effect of change in the secondary resistance on the polyphase speed-torque curve is to change the slips but not the maximum torque. The difficulty, however, in the polyphase tests available was that apparently the resistance had varied very considerably during the tests, especially at the points of high slip, where the secondary losses were very large. As a result the speed-torque curves

corresponded to those of motors in which the resistance increased as the load and slip increased. As a consequence, the torques below the zero speed line were considerably too large, which meant that in applying these curves to the above method, the back torques were presumably entirely too great, thus apparently introducing errors in the derivation of the resultant single-phase curve.

The effect of these discrepancies are shown in Fig. 20. Here, *A* shows the speed-torque curve as it should be at constant temperature, whereas, *B* shows the curve with the resistance of the secondary increasing with increased slip. The corresponding current-torque curves are also shown. A consideration of these curves would seem to indicate that the resultant single-phase curves derived from *A* and *B* should differ somewhat.

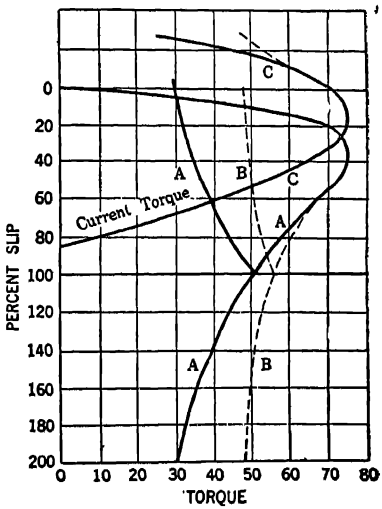


FIG. 20

It was then decided to make a more accurate set of tests on a 10 h.p., 60-cycle four-pole, three-phase motor of the wound-secondary type, so that the secondary resistance could be varied if so desired. It was also decided to obtain a test with two similar motors rigidly coupled together, with their individual primary windings in series, but with their secondaries independent. As already explained, the theory of the foregoing method calls for *equal currents* in the two oppositely rotating fields. This condition is automatically obtained by coupling two primaries in series with each other.* With this arrangement, if the power factors of the two motors were always equal, then it should be equivalent to the method already described. However, these are practically never equal except at the standstill position, although an analysis of the problem shows that the two primary voltages, with this series arrangement, are not greatly out of phase with each other over a very large part of the working range. The writer has not yet sufficiently analyzed the series arrangement

*In reviewing an early draft of this paper, this suggestion, with a number of other most excellent ones, was made by Mr. R. E. Hellmund. However, it developed later that this same suggestion appeared about twenty years ago in Mr. B. A. Behrend's book, "The Induction Motor."

to be sure that it exactly represents all the conditions of the two rotating fields in the single-phase motor, but is inclined to think that such is the case. However, the approximate method developed in this paper lends itself so readily to calculation, that it was considered worth while to check it up carefully by test to see what degree of accuracy could be obtained.

The following series of tests was planned:

(1) Three-phase speed-torque and primary current curves at 220 volts with one motor alone, with its secondary short-circuited on itself.

(2) Single-phase speed-torque and primary current curves on the same motor as (1) at 220 volts and with the secondary short-circuited on itself.

(3) Three-phase speed-torque and primary current curves on the same motor and at same voltage, but with external resistance in the secondary circuits.

(4) Single-phase speed-torque curves under same conditions as (3).

(5) Speed-torque and primary current curves with two similar motors with their primary windings coupled in series, and with the secondaries independently short circuited on themselves, one of these motors to be that used in tests (1) and (4)

(6) Similar tests to (5), but with resistance in the secondaries as in (3).

In carrying out these tests, the torque was measured by a special dynamometer brake, the power absorbing element of which consists of a special separately-excited direct-current machine. Below zero speed, power was supplied to the direct-current machine in order to obtain negative rotation.

Difficulties in obtaining consistent tests, especially at negative speeds, soon developed, due to variations in temperature. With the very heavy currents at low and at negative speeds, the motor would heat so rapidly that all kinds of speed-torque readings could be obtained. Test after test was made and while these would agree very well for the higher speed points where the heating was small, they showed all kinds of inconsistencies for the negative speeds, in particular. The currents for these speeds also showed very wide discrepancies Eventually it was found that those tests taken with extreme rapidity, and which covered only a comparatively small number of points, would plot in quite reasonable curves above zero speed, so that the writer was enabled thus to obtain quite consistent curves

for both torque and current between 1800 rev. per min. and standstill. Not only were the curves, consistent in themselves but those taken with different secondary resistances were fairly consistent with each other. It then remained to obtain reasonable readings for the negative speeds. Obviously it was wrong to take a large number of test points and then draw an average curve through them, for it is evident that the errors, due to heating, tend to throw the torques and currents to one side of the proper curves. Consequently the correct curves should really be boundary lines rather than averages. It was noted, in particular, that heating did not appear to affect the speed to the same extent as the torque at very large slips, and, consequently, by plotting the current in terms of speed rather than torque, less erratic curves were obtainable, and it was possible to plot speed-current curves which were quite consistent for the different conditions of secondary resistance. Furthermore, from the speed-torque and speed-current curves above the zero line, which appeared to be reasonably correct, as they were consistent with each other, it was possible to derive the constants for the general equations for speed-torque. It was found that such derived equations fitted these curves quite accurately and, moreover, they held the proper relation of constants for both high- and low-resistance secondaries The various agreements between the calculations and the tests for the higher speeds were such that one could assume that the derived equations were practically correct and that from them the curves for the negative speeds could be plotted with fair accuracy. In this way the curves for the negative speeds were first obtained and it then remained to check them by actual test. Finally a method of testing was tried which appeared to give quite good results. This consisted in setting the apparatus at about the desired speed and torque conditions; then cooling the motor down to the required temperature preparatory to obtaining the desired test, the power was then thrown on and readings obtained in the shortest possible time, five seconds, for instance. Allowing the motor to run, additional readings were obtained at five second intervals. A series of consecutive readings, at definite intervals apart, was thus obtained and plotted in a curve. By extending this curve back to the instant of starting, results were obtained which were undoubtedly quite close to those corresponding to the starting temperatures, and were not only quite consistent with each other, but also plotted very close to the negative exten-

sions of the calculated curves. As a result of a series of tests extending over several weeks, data was obtained which plotted in curves which agreed fairly well with each other throughout.

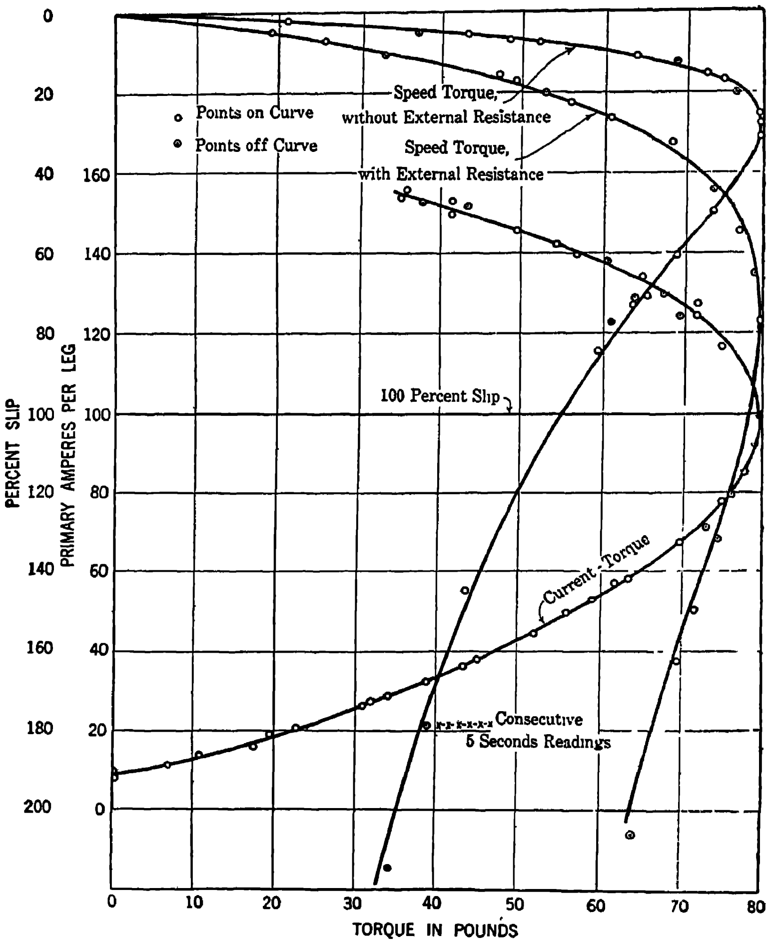


FIG. 21

RESULTS OF TESTS

Polyphase Speed-Torque, Speed-Current and Current-Torque Curves

In Fig. 21 are shown the polyphase speed-torque and primary current both with the secondary short-circuited, and with resistance added In the speed-torque curves the circled points

torque test was selected in which no correction had been made for temperature and where the conditions were quite closely comparable with those of the single-phase tests. From the speed-torque and current data of this polyphase test, the resultant single-phase speed-torque curve was calculated, making no attempt at corrections of any sort. This speed-torque curve is represented by the small squares in Fig. 23. This lies much closer to the tested single-phase curve, thus indicating that temperature is possibly an explanation of a considerable part of the discrepancy between the calculations and the tests. This would

TABLE II.

Slip		Torque at full voltage		Primary amperes per leg at full voltage		$X =$		Reduced torque		Resultant torque
For positive speeds	For negative speeds	T_f	T_b	I_f	I_b	$\frac{I_b}{I_f+I_b}$	$1-x$	Forward	Back	
0 02	1.98	8.2	64 3	12 5	134 2	0.915	0 085	6 9	0 5	6 4
0 05	1 95	18.9	64 8	18 0	133.8	0 881	0 119	14 7	0 9	13.8
0 10	1 90	33 3	65 4	28 0	133.0	0 826	0 174	22 5	2 0	20.5
0 15	1 85	41 5	66 1	37 0	132.3	0 781	0 219	27.5	3 2	24.3
0 20	1 80	53 1	66 9	46 0	131 5	0 740	0 260	29 3	4 5	24 8
0 25	1 75	59 8	67 6	53 0	130 8	0 712	0 288	30.3	5 6	24 7
0 30	1 70	65 1	68 4	60 0	130.0	0 684	0 316	30 5	6.8	23 7
0 35	1 65	69 2	69 1	66.0	129.0	0 662	0 338	30 4	7 9	22 5
0.40	1 60	72.2	69 9	71.2	128 0	0 643	0 357	29.9	8 9	21 0
0.50	1 50	76 5	71.4	81 0	125.5	0.608	0.392	28.2	11.0	17 2
0 60	1.40	78 7	72 9	88.0	122 7	0 582	0 418	26.6	12 7	15 9
0 70	1.30	79.6	74.4	94.0	120 0	0 561	0 439	25 0	14 4	10 6
0.80	1 20	79 6	75 9	99.5	118.1	0 542	0 458	23.4	15.9	7.5
0 90	1.10	79.2	77.8	104.0	112.2	0.519	0.481	21.4	18 0	3 4
1 00	1.00	78 9	78 9	108 2	108 2	0 50	0 50	19.7	19 7	0

also indicate that heat effects as referred to in connection with Fig. 20 are not as objectionable as anticipated However, the writer does not believe that all the discrepancy is due to heating, but considers that this approximate method of dealing with the problem makes the back torque too small. In the arrangement with two motors in series, as mentioned before, the voltages of the two motors will not usually add up directly to give the line voltage, and the motor which represents the back torque, will have a relatively larger percentage of the total voltage than is the case with the above method of considering the problem. This will be considered further under the two-motor tests.

Unfortunately, due to the very short time available, it was not possible to make any extended tests on single phase with a view to correcting for temperature In consequence, the calculated single-phase speed-torque curve, which is on the basis of constant temperature, is compared with tested curves in which no temperature correction has been made. It, therefore, is not known in this case how much of the discrepancy is due to temperature.

In Table II is shown data similar to that of Table I, but for the tests with resistance in the secondary. It will be noted that the resultant of the forward and back torques is considerably lower than in Table I, which is consistent with the fact that in-

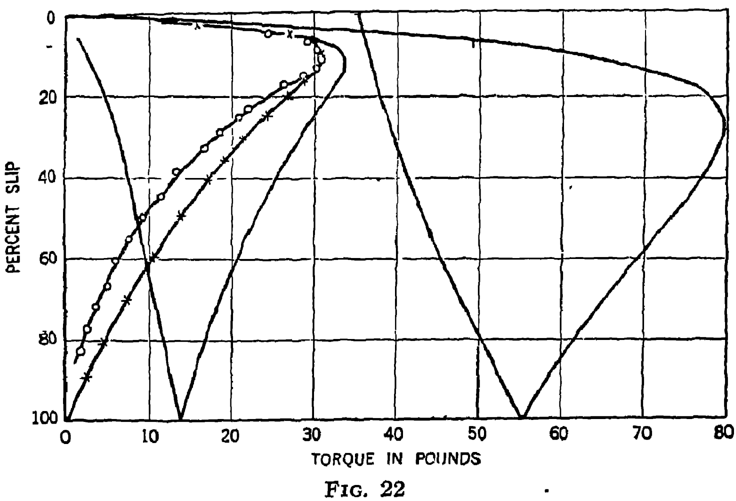


FIG. 22

creased secondary resistance reduces the maximum torque of the single-phase motor.

In Fig. 23 is shown the calculated single-phase speed-torque and the tested torques of the motor with resistance in secondary. Here the circled dots represent the actual test readings and the crosses represent the points obtained from the last column of Table II. The discrepancies are somewhat smaller than in the motor with short circuited secondary. This should be the case, if heating is responsible for any considerable part of the discrepancy, for the currents are relatively smaller.

In order to get a crude idea as to how much of the difference may be due to this feature of temperature, a polyphase speed-

represent actual test readings, while the solid line covers the points calculated from the derived equations.

In Table I, covering data on the short-circuited-rotor tests, are shown the forward and back torques and the corresponding forward and back currents for the various speeds between zero and 200 per cent slip, as derived from Fig. 21; also the calculated values of the ratio of voltages, x and $(1 - x)$, by which the forward and back torques should be reduced in order to get the equivalent single-phase speed-torque curve. The corresponding reduced values for the forward and back torques are also given as calculated from the values x and $(1 - x)$. The last column shows the difference between the reduced forward and back torques, which should represent the single-phase torque, according to the foregoing analysis.

TABLE I

Slip		Torque at full voltage		Primary amperes per leg at full voltage		$X =$		Reduced torque		Resultant torque
For positive speeds	For negative speeds	T_f	T_b	I_f	I_b	$\frac{I_b}{I_f+I_b}$	$1-x$	Forward	Back	
0 02	1 98	20	35 8	19 0	154 8	0 89	0.11	15 8	0 4	15 4
0 05	1 95	41	36 3	34 0	154 5	0 819	0 181	27.5	1 1	26 4
0 10	1 90	61 7	36 9	55.5	154 0	0 735	0.265	33 3	2 6	30.7
0.15	1 85	71 6	37 7	71 0	153 5	0.684	0 316	33 5	3 8	29 7
0 20	1 80	77 3	38 3	85.0	153 0	0 643	0 357	31 9	4 9	27 0
0 25	1 75	79 4	39 2	96 0	152 5	0 614	0 386	29 9	5 9	24 0
0 30	1 70	79.6	39.9	104 0	152 0	0 594	0 406	28 1	6 6	21.5
0.35	1.65	78 8	40 8	110.0	151 5	0 580	0.420	26 5	7 2	19 3
0.40	1 60	77 6	41 6	113.0	151.0	0 572	0.428	25 4	7 6	17 8
0 50	1 50	74 0	43 6	121.0	150 0	0.554	0 446	22 9	8 7	14 2
0 60	1 40	70 0	45 5	128.0	149 0	0 538	0.462	20 3	9 7	10 4
0 70	1 30	65.9	47 8	133 0	147 3	0 526	0.474	18 2	10.8	7.4
0 80	1 20	62 1	50.0	136 5	145.5	0 516	0 484	16 6	11 7	4 9
0 90	1 10	58 8	52 7	139 5	143 5	0.507	0 493	15 1	12 8	2 3
1 00	1 00	55 5	55 5	141 5	141 5	0 50	0 500	13 9	13 9	0

In Fig. 22 are shown the single-phase speed-torque and current-torque curves with short-circuited secondary, as plotted from Table I, and checked by actual test. The circled dots represent actual test points, while the crosses represent points plotted from the last column in Table I. The agreement of test and calculated values are as close as can really be expected considering the difficulties in obtaining the data, and the possible errors.

Two Motors in Series

In Table III is shown the test data and the calculations derived therefrom, for two motors with their primaries in series and with their secondaries short-circuited independently In this test no external resistance was used in the secondaries. Considerable difficulty was encountered in making this test, due partly to bad alignment of the machines, as they were rigidly coupled together. Furthermore, in several of the earlier tests, the effects of temperature were disregarded and all indications were that the secondaries were quite hot during the tests. There was so much discrepancy between the various results that the

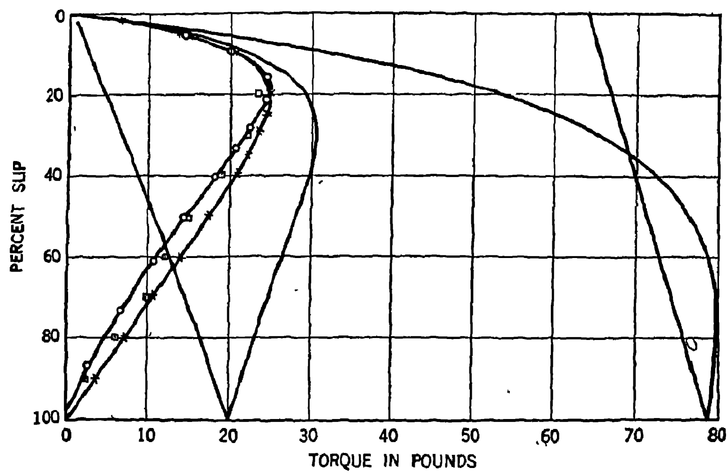


FIG. 23

writer cannot feel sure of the data shown in this table, although it was obtained under quite careful conditions of test.

In the above table the percentage of line voltage applied to each motor is shown. It is of interest to compare these percentages with those shown in Table I. This is illustrated in Fig. 24. This shows that the percentage of voltage on the forward rotating motor is higher at the higher speeds, than in Table I, but is lower at the low speeds. On the other hand, the voltage on the backward-rotating motor is higher at all speeds than in Table I. Thus, the back torque has always a higher value than in Table I. Consequently, with the reduced forward torque at the lower speeds and the higher back torque, the resultant torque

TABLE III.

Speed		Torque corrected to 220 volts	Volts			Ratio of motor to line volts		Polyphase torque at 220 volts		Polyphase torque at reduced voltage		Resultant torque
r. p. m.	Slip		Line	No. 1 motor	No. 2 motor	No. 1 motor	No. 2 motor	Forward	Back	Forward	Back	
300	0.833	1.5	218.5	109 2	110 5	0.506	0 505	61 0	51 4	15 6	13 1	2 5
600	0.667	2.5	217.0	110.9	107.5	0 511	0 495	67 0	47 0	17 5	11 5	6 0
800	0.556	4 9	218.5	115 8	106.8	0 530	0.488	71.5	44 5	20 9	10.6	10 3
1000	0.444	8.3	219 0	118 4	105.0	0 541	0.48	76 0	42 4	22 2	9 8	12 4
1100	0.389	9.7	219.0	121.2	102.5	0.553	0.468	77.9	41.4	23.9	9 1	14 8
1200	0.333	12.3	219.0	124.5	100 0	0 569	0.457	79.2	40.3	25 6	8 4	17 2
1300	0.278	15.5	219.0	126.5	100.0	0 578	0.457	79.6	39.3	26.5	8 2	18 3
1400	0.222	19.6	220.0	133 4	94 0	0 605	0.427	78 8	38.5	28.9	7.1	21.8
1500	0.167	24.4	220.0	152 5	88.0	0.693	0 400	74 5	37.6	35.8	6.0	29.8
1580	0.122	27.6	220.0	157.7	78 0	0.717	0.355	67.0	37.0	34.4	4.7	29.7
1620	0.100	27.9	221.0	166 4	70 0	0 753	0 317	62.0	36.7	35 1	3 7	31.4
1660	0 078	29.2	221.0	173.2	62.5	0.784	0.283	54.5	36.3	33 5	2 9	30.6
1700	0.056	26.1	221.0	187.2	52 5	0.847	0.238	44.0	36.0	31.6	2 0	29 6
1740	0.033	19.9	222.5	195.5	36.0	0.879	0.162	31 0	35.7	23.9	0 9	23.0
1780	0.011	10.	223.0	202.8	25.0	0 909	0.112	14 0	35.4	10 3	0 4	9.9
1800	0 0	....	224.0	208.0	14.0	0.961	0.062	....	35.3	....	....	....

derived from the polyphase curve will naturally be lower than in Table I, which appears to be the case in all the tests made.

The data in Table III indicate that the two motors have their

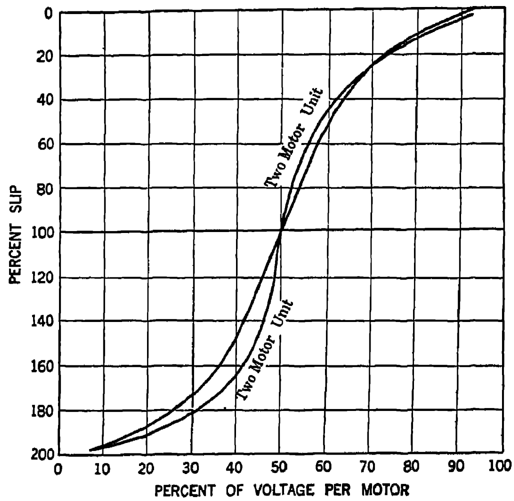


FIG. 24

primary voltages very nearly in phase at all times. The sum of the two motor voltages is never much greater than that of the line.

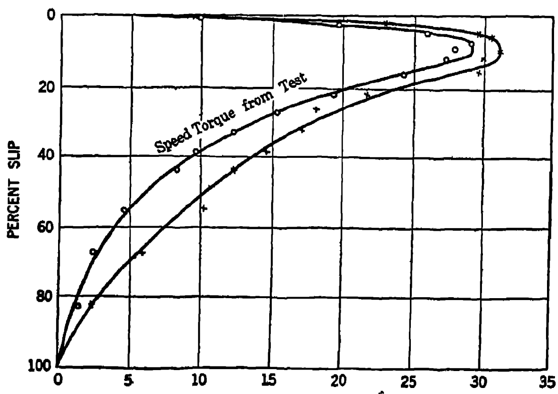


FIG. 25

In Fig. 25 is shown the calculated and test speed-torque results corresponding to Table III. The test result shows lower torques at the low speeds than can be derived from the voltage percent-

TABLE IV.

Speed		Torque corrected to 220 volts	Volts			Ratio of volts		Polyphase torque at 220 volts		Polyphase torque at reduced voltage		Resultant torque
r. p. m.	Slip		Line	No. 1 motor	No. 2 motor	No. 1 motor	No. 2 motor	Forward	Back	Forward	Back	
340	0.811	1.71	219 0	114 3	108 0	0 521	0.493	79 6	76 1	21 6	18 5	3 1
480	0 734	4.93	219.0	117.8	105 0	0 538	0 480	79 7	75 0	23 0	17 3	5 7
640	0 645	7 85	219 0	122 1	102 0	0 552	0.470	79 1	73 5	24 1	16 2	7.9
810	0 555	11 2	219 5	126.4	98 0	0 576	0 446	77 8	72 0	25 8	14 3	11 5
1010	0 439	15 25	219 5	134 2	93 0	0.612	0.424	74 1	70 1	27 8	12 6	15 2
1220	0 322	20 5	220 0	146 3	83.0	0 664	0 377	67.5	68 5	29 8	9 7	20 1
1300	0 278	22 2	220.0	153 3	79 0	0 697	0.359	63.1	67.8	30 8	8 7	22 1
1410	0 217	23.8	220 0	164 5	70 0	0 748	0 318	55.5	66 9	31 1	6 8	24 3
1500	0 167	23 1	220 0	174 0	61 0	0 791	0 277	48 0	66 3	30 5	5 1	25 4
1600	0.111	20 1	220 5	187.0	47 0	0 848	0 213	36.5	65.5	26 3	3 0	23 3
1700	0 050	12 6	221.0	199 2	30 0	0 90	0 136	31.0	64 6	17 0	1 2	15 8
1750	0.028	6 0	221.0	204 4	24 0	0.925	0 109	12.0	64 3	10 3	0 8	9 5
1780	0 011	3 2	221.0	206 1	17 0	0 933	0 076	6.0	64 0	5 2	0 4	4 8

ages applied to the polyphase torques Part of this difference may be due to temperature conditions.

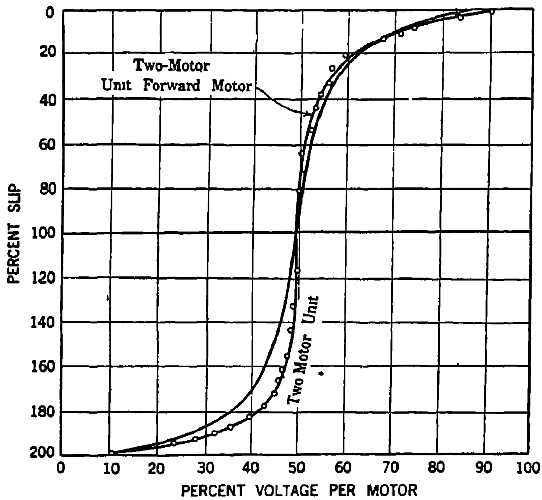


FIG. 26

In Table IV is shown the corresponding data for two motors with resistance in the secondary. Under this condition the various tests made were more consistent with each other and

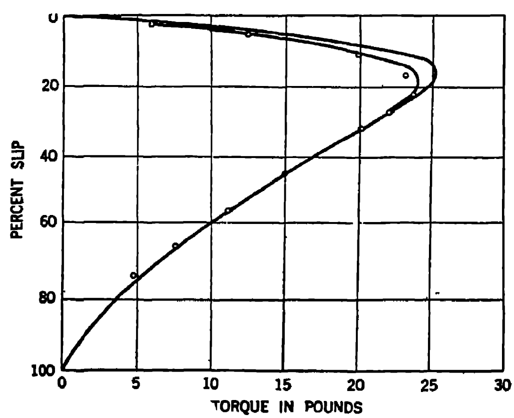


FIG. 27

the writer has more confidence in the data than in the case of Table III.

In Fig. 26 is shown the percentages of line voltage on each of

the two motors, compared with those in Table II These show the same differences as in Fig. 24, where there was no external resistance.

In Fig. 27 is shown the speed-torque curve for both calculation and test, as taken from Table IV. Here the discrepancies are much smaller than in Fig. 25.

Conclusion

While the data is not as exact as the writer would desire, yet he feels that the general results obtained from the various tests have indicated that the method of analysis followed in this paper is along proper lines and that this conception of the action of the single-phase induction motor is of considerable assistance in obtaining a proper understanding of the machine. As stated before, the primary purpose of this paper is not to develop a method of calculation, but is simply to illustrate some of the characteristics of the single-phase motor. It is hoped that this will bring out more clearly the very intimate relation between the polyphase and single-phase induction motors in their operating characteristics.

SINGLE-PHASE LOADS FROM POLYPHASE SYSTEMS

FOREWORD—This paper was presented at the thirtieth annual convention of the Association of Edison Illuminating Companies, held at White Sulphur Springs, Va , September, 1914. Its purpose was to show some of the possibilities of phase conversion from polyphase to single-phase, in view of the increasing requirements for single-phase service for electric furnace work and various other special applications. The paper deals with some of the problems of synchronous phase balancers, etc.—(ED.)

THE broad statement may be made that *it is not practicable to transform a polyphase load to single-phase by means of transformers alone*. There is a definite, positive reason for this, namely, a single-phase load represents power which is pulsating or varying periodically from zero to a maximum value, while a balanced polyphase load represents continuous power of constant value. It is obviously not feasible to transform from continuous power to pulsating, or vice versa, without some means of storing and restoring power, which is not practicable with transformers.

Keeping the above statements in mind, it is obviously a waste of time to attempt to accomplish the result by special transformer connections or arrangements. However, many attempts have been made to produce this result with transformers alone, and some with superficial evidence of success—that is, in some cases, it has been possible to load the three phases equally *in current* when delivering single-phase load. But balanced currents in this case do not mean balanced power loads, nor do they, as a rule, mean less total loss in the generator windings. In fact, the equality of the currents in the different leads is obtained simply by out-of-phase currents, part of them usually being leading and part lagging. The resultant reactions and unbalancing effects of these leading and lagging currents have precisely the same effect on the generating system as the single-phase alone would have.

On the basis therefore of storing and restoring power in order to obtain balanced three-phase loads when delivering single-phase, various possible methods of accomplishing this result may be considered. The obvious method is by means of a motor-generator in which a three-phase motor drives a single-phase generator, the entire single-phase load being transformed from electrical to

mechanical, and then back to electrical. Where entire independence of the single-phase and three-phase currents is desired, this of course, is the ideal method. On the other hand, it is possibly the least efficient method. But where both change in frequency and change to single-phase load are involved without distortion of the polyphase load conditions, then double transformation of power appears to be necessary, such as from electrical to mechanical and back to electrical, or from electrical to some other form of electrical power, involving a second complete transformation. The motor-generator is an example of the first, while transformation from three-phase to direct current by a rotary converter, and from direct current to single-phase of another frequency by a second converter, is an example of the second.

Where the power-factor of the load is low, as in some electrical furnace systems, one advantage of the motor-generator method is that the power-factors of the supply system and the load are absolutely independent of each other.

However, where the transformation from three-phase to single-phase is at the same frequency, it would appear that part of the single-phase load could be delivered directly from one phase of the three-phase system, while the other part of the load could be taken from the other phases and re-transformed in phase by rotating apparatus to that of the single-phase load, so that only part of the load would thus need transformation. For instance, assume that one-third of the single-phase power is taken from one phase, and the other two phases supply power to a suitably wound motor, which drives a single-phase generator having the same phase relation as the third circuit of the three-phase system. Obviously, the generator could feed its single-phase load in parallel with the other single-phase circuit. The three generator circuits would thus be equally loaded and the single-phase generator of the motor-generator set would not be transforming the full single-phase load. This illustrates the principle of transforming from three-phase to single-phase without transforming the whole load, but this particular arrangement of apparatus is not a very practical one. But the question naturally arises whether this cannot be done in comparatively simple manner by means of a single machine, connected across the three-phase circuit, which will serve to transfer power from part of its circuits to others at a different phase relation. This principle has been utilized in the past to transform from single-phase to polyphase, and in the same apparatus the

operation has proven to be reversible. It may, therefore, be considered as settled that such transformation is possible and practicable.

Fundamentally, the action of phase balancing is as follows:—When a single-phase load is taken from a polyphase circuit, it tends to distort the phase relations in the latter circuit. Any synchronous or induction type polyphase motor connected to a distorted polyphase circuit will act in such a way as to have a balancing effect on its supply system. Any such motor will naturally tend to do this, for the motor, with its own balanced phase relations will tend to take current and load in accordance with the supply voltages—that is, it will tend to take more from the higher voltages, and if the power taken from the higher circuits exceeds the load or losses of the motor itself, then the excess is fed back into

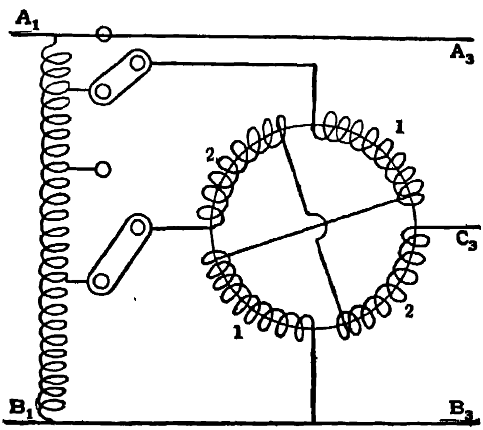


FIG 1—SCHEME OF CONSTRUCTION FOR CONVERTING FROM SINGLE-PHASE TO BALANCED THREE-PHASE

the lower voltage circuits. It thus has a balancing action on the supply circuit. This is the natural tendency of all polyphase synchronous and induction types of rotating machines when connected to a supply circuit. However, in the motor itself, this tendency to correct the unbalancing of the supply circuit will be accompanied by a corresponding tendency inside the motor itself to distort its own internal phase relations until they match those of the supply system. But if the distortion of the phase relations inside the motor can be prevented or neutralized in any manner, then the motor will transfer loads between its phases or circuits to such an extent that it will correct the unbalancing of the poly-

phase system. In other words, if balanced three-phase potentials are held at the point of delivery of single-phase load, then the three-phase supply system, up to that point, will be balanced. The operation of the various phase-balancing methods therefore lies in correcting the effects of the internal phase distortions in the phase-balancing motor, whether it be of the induction or of the synchronous type.

The action of a phase-converting device in a simple form can probably be shown best by an arrangement used in railway work for converting from single-phase to balanced three-phase, and from three-phase to single-phase when acting regeneratively.

Fig. 1 illustrates such an arrangement, consisting of a transformer, a phase splitter, and single and three-phase circuits. The transformer is connected across the single-phase circuit, which, for simplicity, also is shown as one phase of the three-phase circuit. The phase splitter has one phase connected across the same phase

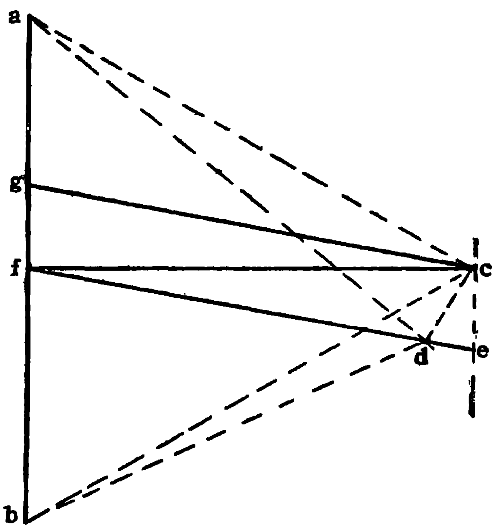


FIG 2—VOLTAGE CONDITIONS IN THE CIRCUITS INDICATED IN FIG 1 WHEN TRANSFORMING SINGLE-PHASE TO THREE-PHASE

as the transformer; while its other phase, which is wound in 90-degree relation to the former, has one end connected to some intermediate point of the transformer, and its other is connected to the third phase of the three-phase circuit.

The voltage relations, both without and with load, when transforming to three-phase, are indicated in Fig. 2. In this

diagram, *ab* represents the single-phase e. m. f. delivered to the transformer. The line *fc* represents the e. m. f. generated in phase 2 of the phase splitter, this being 86.6 percent of *ab*. Therefore, with *fc* at right angles to *ab*, lines *ac*, and *ab* are equal, and a balanced three-phase circuit is obtained at the three-phase terminals.

Next, assuming that a three-phase load is carried, then, due to internal distortions, *fc* is both reduced in value and shifted in phase to the position *fd*. The three-phase voltage relations are then indicated by *ab*, *ad* and *bd*. To correct this distorted condition, assume (1)— that the e. m. f. across phase 1 of the phase converter is increased sufficiently to increase the e. m. f. of phase 2, so that it will be represented by *fe*, instead of *fd*, the increase being such that a line connecting *c* and *e* will be parallel with *ab*. Then assume (2) that the connection at *f* is moved along *ab* to a point *g* such

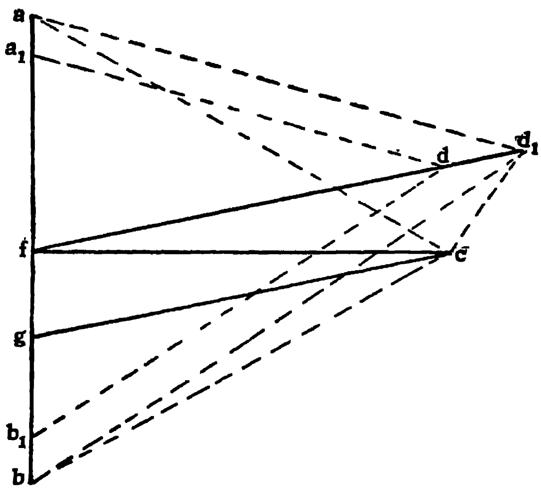


FIG. 3—VOLTAGE RELATIONS WHEN TRANSFORMING THREE-PHASE TO SINGLE-PHASE

that *fg* equals *ce*. This brings terminal *e* to the position *c*, and the internal phase relations will then be such that balanced e. m. f.'s, corresponding to *ab*, *ac* and *bc*, will be delivered to the three-phase circuit when carrying load, and the three-phase circuit will necessarily carry balanced three-phase load, although the source of power is single-phase.

In Fig. 3 is shown a similar arrangement, except that the transfer of power is from three-phase to single-phase, using the

same apparatus as in Fig. 2. As in Fig. 2, *ab*, *ac* and *bc* represent three-phase balanced voltages, or the no-load condition. With load, the conditions are the reverse of those in Fig. 2. The voltage *fc* is shifted in phase with respect to *ab*, but in the opposite direction. Also *ab* is shortened with respect to *fc*. The unbalanced phase relations can therefore be represented by the triangle a_1, b_1, d. Therefore, if a_1b_1 is to be maintained at the value *ab*, then *fd* will be increased proportionately to fd_1, and the relations are represented by the triangle abd_1. This triangle therefore has to be corrected to correspond with the balanced diagram *abc*. This can be done by (1) reducing the e. m. f. of phase two of the phase converter (by reducing phase one, for instance), and by (2)— moving *f* to g. This brings d_1 in coincidence with *c* and a balanced three-phase condition then results.

It is obvious in Fig. 2 that the addition of an e. m. f. at the terminal *d* corresponding in value and direction to the line *cd* would have corrected to a balanced condition for the assumed load and power-factor. Also, in Fig. 3, a correcting e. m. f. d_1c would have accomplished the desired result. In the actual diagrams, instead of supplying this correcting e. m. f. directly, it was obtained indirectly by combining two right angle e. m. f.'s of suitable value and direction, these two being readily obtainable in the arrangement shown. However, the illustration shows how a single correcting e. m. f. of proper phase and value can correct from a distorted three-phase system to a balanced system.

Instead of the above special arrangement for changing from three-phase to single-phase, any standard type of three-phase motor, either synchronous or induction, could be used for phase balancing by the addition of a suitable correcting e. m. f. in one of the phases, and if this correcting e. m. f. is of such value and direction as to maintain balanced e. m. f.'s across the three terminals, then the phase-balancing motor will correct the single-phase load.

If an induction motor is used as a phase balancer under the above conditions, then it will simply serve as a phase converter, but has no ability to correct or adjust the power-factor. If the phase balancer is of the synchronous type, however, it can be adjusted and controlled to act as both a phase converter and a power-factor corrector. If the single-phase load to be carried is at a relatively low power-factor, then it will exert a demagnetizing effect upon the phase balancer which must be taken into account

when the e. m. f phase relations are adjusted for proper balancing. This means that the field excitation of the phase balancer must be increased sufficiently to overcome the demagnetizing tendency of the single-phase load. This increase in field excitation will tend to increase the e. m. f.'s of all the armature circuits but, as one winding, when balanced conditions are obtained, will carry practically all the wattless current corresponding to the single-phase load, while the others will be carrying power only (on the assumption that 100 percent power-factor is maintained on the three-phase system) the effect of the internal self-inductions of the phase balancer will be such that the resultant e. m. f.'s of some of the windings will be increased to a greater extent than others when the field excitation is increased. Therefore, when correcting for inductive loads, a different value and direction of the correcting e. m. f. is necessary than would be required for single-phase loads without power-factor correction.

It is obvious from the above that what is needed for obtaining balanced conditions and corrected power-factor on the polyphase system when carrying a low power-factor single-phase load, is a suitable synchronous motor acting as a phase balancer in connection with some auxiliary means for introducing a correcting e. m f. which should vary in value and direction with the load and power-factor.

There are various ways by which this result can be accomplished. To illustrate: It may be assumed that the desired correcting e. m. f. may be obtained by means of a small synchronously running booster which is connected in series with one phase of the phase balancer. The value of this e. m. f. can be varied by varying the field excitation of the booster field. The phase relation of this booster e. m. f. can be regulated in various manners, as, for instance, by mechanically shifting the field structure circumferentially with respect to the armature. Or, the armature of the booster might have two fields side by side, but with their poles displaced circumferentially 90 degrees with respect to each other. Then, by separate adjustment of the excitations of the two fields up and down, or reversed, the e. m. f. generated by the booster armature can be given any desired direction or value. Or, instead of two fields side by side, a single field structure can be used in the booster, with two exciting windings overlapping or displaced 90 degrees with respect to each other, like the primary windings of a two-phase induction motor. By proper adjustment of the excit-

ing current in these two windings, the same results as with two fields side by side may be obtained. With the booster e. m. f. thus under control, it is obvious that any desired phase or voltage correction can be obtained in the phase balancer. There are various other ways of obtaining the corrective e. m. f., such as by induction regulators, etc., but the above is sufficient to illustrate the general arrangement or method of operation. Mr. E F. W Alexanderson* has also proposed a method of accomplishing this result.

The very considerable complication of such methods of phase balancing may be necessary where widely fluctuating loads and non-related variations in power-factor are encountered. In such cases, automatic voltage regulations can be used in connection with the main and the booster fields to obtain the desired corrective action. However, combination of the synchronous machine and its booster, or boosters, requires, as a rule, considerably less total apparatus than a straight motor-generator, and the losses should also be materially less.

However, where the single-phase load conditions are not too widely fluctuating, it is possible to use much simpler arrangements. In electric furnace work the single-phase load and power-factor may be almost constant when the load is on. In such cases, phase splitting may be accomplished in a fairly simple and effective manner by a single synchronous machine, either with or without a small additional autotransformer, and with suitable taps and switches for varying certain voltage relations.

In synchronous phase balancers there is a very considerable magnetic action on the field poles and structure by the armature winding when carrying load, unless the field poles are equipped with ample cage dampers similar to those required on the fields of large single-phase generators. If these dampers are of proper proportions, the pulsating effect of the armature on the field can be suppressed with comparatively small loss in the dampers. However, the alternative of such machine, namely, the straight motor-generator, must also have heavy dampers on its single-phase element, so this does not change the relative efficiencies of the two methods.

When power-factor correction is required, as well as phase balancing, then the size or capacity of the phase balancer will depend to a certain extent upon the amount of power-factor

*Phase Balancer for Single-Phase Load on Polyphase Systems," by Mr. E. F. W. Alexanderson. General Electrical Review, December, 1913.

correction. As it may be of interest to know what capacity of phase balancer is required in terms of single-phase load, the approximate curves shown in Fig. 4 have been worked out for different power-factors, showing the capacity (three-phase) required in phase balancers for each 1,000 k.v.a. single-phase load taken off. The ordinates represent power-factors of the single-phase load, while the abscissae show the k.v.a. ratings of the phase balancers required at various three-phase power-factors. The phase balancing k.v a. is given in terms of three-phase capacity—that is, the capacity which the machine would have as a three-phase generator, with a current rating corresponding to the largest of the unbalanced currents in its three phases. In other words, this rating is on the basis of maximum local losses, instead of averaging, and thus represents the most severe condition. The capacity of the booster or other apparatus for supplying the correcting e. m. f. is not included. This can be assumed roughly as about 15 percent of that of the phase balancer, whether it is a separate piece, such as a separate booster or transformer, or is obtained in the balancer windings.

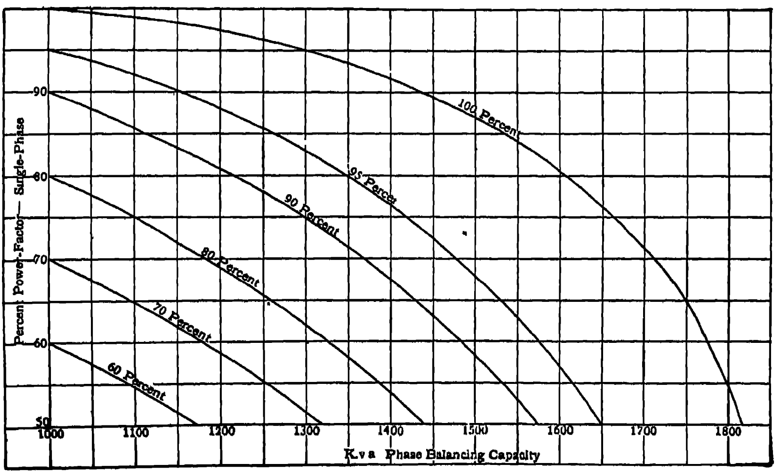


FIG. 4—CURVES SHOWING THE BALANCING CAPACITY REQUIRED (THREE-PHASE) FOR EACH 1 000 K.V.A. OF SINGLE-PHASE LOAD

These curves show that usually there is considerable saving in capacity of apparatus in the use of a phase balancer, as compared with a straight motor-generator where power-factor correction is not important. For example, assume a single-phase load is at 70 percent power-factor, while the corresponding three-

phase balanced power is to be held at the same power-factor. From the table, the approximate capacity of the phase balance is 1,000 k.v.a. Adding 15 percent for the booster, gives 1,150 k.v.a. as the total balancing capacity required. Comparing this with a straight motor-generator, the driving motor will have a normal capacity of 700 kw approximately, while the 1,000 k v.a. single-phase generator would approximately correspond in capacity to a 1,500 k.v.a. three-phase machine—thus requiring a total of 2,200 k.v.a., compared with 1,150 k.v a. for the phase balancer. The latter means, therefore, materially less expensive apparatus—also more efficient. It may be noted throughout that where there is no correction of power-factor, the balancer capacity in k.v.a. will be equal to the k v.a. of the single-phase load. If, however, in the above example, 70 percent single-phase power-factor is to be corrected to 90 percent in the three-phase circuit, then the balancer capacity will be 1,390 k.v.a. Adding 15 percent for the correcting booster gives 1,600 k.v.a. against 2,200 k.v.a. for the motor-generator.

The phase balancer therefore apparently does not correct for power-factor as advantageously as the straight motor-generator. Also, where automatic correction of power-factor is desirable, the motor-generator arrangement is somewhat less complicated.

THE TECHNICAL STORY OF THE FREQUENCIES

FOREWORD—This paper was presented before the Washington Section of the American Institute of Electrical Engineers in January, 1918. It covers briefly the history of the various frequencies used in America and the engineering and technical reasons which have influenced their ultimate choice or rejection. The author had in mind the preservation of this in more or less historical form, in order that it should not eventually be entirely lost. Since the publication of this paper, the author has received many favorable comments on it, as being the only reliable source of information on the subject which is now available. It has been reprinted in its entirety in a number of technical papers and the material drawn from it has been used in a number of technical lectures by various engineers and educators.—(ED.)

IN the early days of the alternating current, there were no well established tendencies toward any definite frequencies, either in this country or in Europe. Each manufacturer selected that frequency which best suited his particular style of generating apparatus, and the greater the number of manufacturers, the greater the number of frequencies. But quite early, in America, there developed definite tendencies toward certain standards. Later, similar tendencies in Europe operated to bring about a general adoption of a limited number of definite frequencies.

It is not the purpose of the paper to deal with the history of any but the American tendencies and developments, as these form a sufficient story in themselves.

The story of how and why the various commercial frequencies came into use and then dropped out again, in most cases, is not primarily the story of the frequencies themselves, but of the various uses to which the alternating current has been applied. In other words, fundamental changes in the application of alternating current have led to radical changes in the frequencies. Some of the applications which have had a determining factor on the frequency of the supply system are as follows; incandescent lighting, transformers, transmission systems, arc lighting, induction motors, synchronous converters, constructional conditions in rotating machinery, and operating conditions. A brief consideration of these items individually,

from the present viewpoint, indicates that while some of them had, at one time, very considerable influence in determining frequency conditions, yet, in a number of cases, the original reasons have disappeared through improvements and refinements, as will be described later.

At various times the following standard frequencies have been in use in this country, namely, 133⅓, 125, 83⅓, 66⅔, 60, 50, 40, 30 and 25 cycles per second. These did not appear chronologically in the order given above, and a few odd frequencies in a few special applications are omitted.

In the following, the various frequencies will be considered more or less in the order of their development and basic reasons will be given for their choice, and the writer will endeavor to show why certain of them have persisted, while others have dropped out. It will also be shown why the commercial situation has first tended strongly toward certain frequencies and afterwards swung toward others.

133 AND 125 CYCLES

In the earliest alternating work, the whole service consisted of incandescent lighting, and the electric equipment was made up of small high-speed belted single-phase generators and house-to-house distributing transformers. As the transformers were of small capacity and as their design was in a very crude state, it was believed that a relatively high frequency would best meet the transformer conditions. A choice of such an odd frequency as 133⅓ cycles per second, is due to the fact that in those early days (1886 to 1893) frequencies were usually designated in terms of alternations per minute. One of the earliest commercial generating units constructed by the Westinghouse company had a speed of 2000 rev. per min. and had eight poles. This presented a fairly convenient constructional arrangement for the surface-wound type of rotating armature, which was the only one recognized at that time. The speed of 2000 rev. per min., with eight poles, gave 16,000 alternations per minute, or 133⅓ cycles per second according to our present method of designation. Thus the earliest frequency in commercial use in this country was fixed, to a certain extent, by constructional reasons, although the house-to-house transformer problem apparently indicated the need for a relatively high frequency. The Thomson-Houston company adopted a standard frequency of 15 000 alternations per minute, (125 cycles) instead

of the Westinghouse 16,000, but the writer does not know why this difference was made. However, the two frequencies were so close together that practically they could be classified as one.

At this time, it should be borne in mind, there were no real transmission problems, no alternating-current arc lighting, no induction motors and the need for uniform rotation of the generators was not recognized. The induction motor, in its earliest stages, came in 1888 and considerable work was done on it in 1889 and 1890, but it required polyphase supply circuits and comparatively low frequency and, therefore, it had no connection whatever with the then standard single-phase, 133⅓ and 125 cycle systems. The synchronous converter was also unheard of (one might say almost undreamed of) at that time.

60 Cycles

In 1889 or 1890 it was beginning to be recognized in this country that some lower frequency than 125 and 133⅓ cycles would be desirable. Also about this time direct-coupled and engine-type alternators were being considered in Europe and it was felt that such construction would eventually come into use in America. It was appreciated that in such case; 133⅓ cycles would present very considerable difficulties compared with some much lower frequency, due to the large number of poles which would be required. For instance, an alternator direct driven by an 80-rev. per min. engine would require 200 poles to give the required frequency and such construction was looked upon as being practically prohibitive. About this time Mr. L. B. Stillwell, then with the Westinghouse company, made a very careful study of this matter of a new frequency, in connection with the possibilities of engine type generators, and after analyzing a number of cases, it appeared that 7200 alternations per minute (60 cycles per second), was about as high as would be desirable for the various engine speeds then in sight. Transformer constructions and arc lighting were also considered in this analysis. While it was deemed that a somewhat higher frequency might be better for transformers, yet a lower frequency than 60 cycles was considered as possibly better for engine type generators. A compromise between all the various conditions eventually led to 60 cycles as the best frequency. However, while this frequency originated about 1890, it did not come into use suddenly, for it was impossible to introduce such a radical change in a brief time. Moreover, the direct-coupled

or engine-type generator was slow in coming into general use and, therefore, there was not the necessity for the introduction of this low frequency in many of the equipments sold from 1890 to 1892. However, by 1893, 60 cycles became pretty firmly established and was sharing the business with the 133⅓-cycle systems. It should be borne in mind that, at this time, the adoption of this frequency was not considered as a direct means for bringing forward the polyphase induction motor, for the earlier 60-cycle systems, like the 125- and 133⅓-cycle, were all single-phase Also, it was then thought that the polyphase motor would possibly require a still lower frequency and, moreover, the polyphase system was looked upon as in a class by itself, suitable only for induction motor work. At that time the introduction of polyphase generators for general service was not contemplated. This followed about two or three years later.

In 1890 the Westinghouse company, which had been developing the Tesla polyphase motor laid aside the work, largely on account of there being no suitable general supply systems for this type of motor. The problem was again revived in 1892, in an experimental way, with a view to bringing out induction motor which might be applied on standard frequencies such as could be used in commercial supply circuits for lighting and other purposes. It should be understood that at this time such circuits were not in existence but were being contemplated. In 1893, after the polyphase motor had been further developed up to the point where it showed great commercial possibilities, the best means for getting it on the market were carefully considered. It was decided that the best way to promote the induction motor business was to create a demand for it on commercial alternating-current systems. This meant that, in the first place, such systems must be created. Therefore, it was decided to undertake to fill the country with polyphase generating systems, which were primarily to be used for the usual lighting service It was thought that, with such systems available, the time would soon come when there would be a call for induction motors. In this way experience would be obtained in the construction and operation of polyphase generators and the operating public would not be unduly handicapped in the use of such generators, compared with the older single-phase types.

An early example of this new practise was in the 2000-kw. polyphase generating units used for lighting the Chicago World's Fair in 1893. Here the single-phase type still persisted, as each

generator unit was made up of two similar frames placed side by side, but with their single phase armatures d splaced one-half pole pitch from each other so that the combined machine delivered two single-phase currents displaced 90 degrees from each other. It was considered that each circuit could be regulated independently for lighting service, and polyphase motors could be operated from the two circuits. These generators (at that time the largest in this country) were designed in 1892 and were of 60 cycles. These, therefore, indicate the tendency at that time toward lower frequency and polyphase generation, although commercial polyphase motors were not yet on the market.

25 CYCLES

At the same time that 60 cycles was selected as a new standard it was recognized that at some future time there would be a place for some much lower frequency, but it was not until two years later that this began to narrow down to any particular frequency. In 1892 the first Niagara electrification, after several years consideration by eminent authorities, had centered on polyphase alternating current as the most desirable system. The engineers of the promoting company had also worked out what they considered the most suitable construction of machine. This involved 5000-h. p. units at 250 revolutions per minute. Prof. George Forbes, one of the engineers of the company had furnished the electrical designs for a machine with an external rotating field and an internal stationary armature. His design used eight poles, thus giving 2000 alterations per minute, or $16\frac{2}{3}$ cycles per second. Quite independently of this, the Westinghouse company, in 1892, had been working on the development of synchronous converters, using belted 550-volt d-c. generators with two-phase collector rings added. The tests on these machines had shown the practicability of such conversion and had even proved at this early date, that the converter copper losses were much lower than in the corresponding d-c. generators. Thus it is an interesting fact that the first evidence of this important principle was obtained from a shop test rather than by calculation. The writer, from an analysis of the tests, which were made under his immediate direction, concluded that the armature copper losses must be considerably lower than in the same machine used as a d-c. generator. He also brought the matter to the attention of Mr. R. D. Mershon, then with the Westinghouse company, and the problem was then worked out mathematically by him

and the writer, in two quite different ways, but with similar results, showing that the converter did have actually very much reduced copper losses.

As a result of this work of the Westinghouse company on the synchronous converter, it was decided that, to make such machines practicable, some suitable relatively low frequency was required. This appeared to be about 30 cycles. About this time the construction of the Niagara generators was taken up with the Westinghouse company to see whether it would construct these machines according to the designs submitted by the promoting company's engineers. These designs were gone over as carefully as the knowledge of such apparatus, at that time, permitted, and many apparent defects and difficulties were pointed out. The Westinghouse company then proposed, as a substitute, a 16-pole, 250-rev. per min. machine (the speed being definitely fixed at 250 rev. per min.). This gave $33\frac{1}{3}$ cycles or as near to the Westinghouse proposed 30 cycle system, as it was possible to get. Then many arguments were brought forward, pro and con, for the two machines and frequencies. Prof. Forbes' preference for $16\frac{2}{3}$ cycles was based partly on the possibilities it presented for the construction and operation of commutator type motors, just as with direct current circuits. The Westinghouse contention was that this frequency was too low for any kind of service except possibly commutator type machines. Tests were made with incandescent lights and it was found that at $33\frac{1}{3}$ cycles there was little or no winking of light, while at $16\frac{2}{3}$ cycles, the winking was extremely bad. Tables were also made up, showing the limited number of speed combinations at $16\frac{2}{3}$ cycles for induction motors, in case such should come into use. This showed how superior the $33\frac{1}{3}$ cycles would be as regards such apparatus. It was also brought out that synchronous converters, when such became commercial, would be much better adapted for the higher frequency, as the choice of speeds would be much greater. From the present viewpoint the arguments appear to have been much in favor of the Westinghouse side of the case.

As a consequence of all this discussion the suggestion was advanced by some one, that a 12 pole, 250-revolution machine, (that is, 3000 alternations, or 25 cycles), might meet sufficiently the good qualities of both of the proposed frequencies and would thus be a good compromise. In consequence a 12-pole, 25-cycle machine was worked up by the Westinghouse company and

eventually this frequency was adopted for the Niagara generators. Afterwards, while these generators were being constructed it was brought out pretty strongly that the great advantage of this frequency would be in connection with synchronous converter operation, but that it was also extremely well adapted for slow-speed engine type generators, which were then coming into use. In consequence of the prominence given this frequency it was soon adopted as a standard low frequency, especially in those plants where synchronous converters were expected to form a prominent part of the system.

However, while 60 and 25 cycles came into use, as described above, it must be recognized that they had competitors. For instance, $66\frac{2}{3}$ cycles (8000 alternations or one-half of 16,000) was used to a considerable extent by one of the manufacturing companies. Also 50 cycles came into use in certain plants and, to a certain extent, is still retained, but has become the standard high frequency of Europe. Instead of 25 cycles, the Westinghouse company advocated 30 cycles for some of its plants, largely because with the 25 per cent higher speeds permissible with such frequencies, the capacities of induction motors could be correspondingly increased and also incandescent lighting was more satisfactory. However, it was soon recognized that the $66\frac{2}{3}$ and 30 cycle variations from the two leading frequencies of 60 and 25 cycles were hardly worth while, and they were gradually dropped, except in plants already installed. A brief attempt was made at a somewhat later period to place 40 cycles upon the market as a substitute for both 25 and 60 cycles. This was done under the impression that 40 cycles would give a universal system for arc and incandescent lighting, transmission, induction motors, synchronous converters and about everything else. This frequency possessed many merits and it was thought, at one time, that it might win out, but apparently the other two frequencies were too well established, and the 40 cycle system eventually lost ground.

The problem of the frequencies finally narrowed down to the two standards, and these two were accepted because it was thought that they covered such entirely different fields of service that neither of them could ever expect to cover the whole. In other words, two standards were required to cover the whole range of service. It was recognized that 25 cycles would not take care of alternating-current arc lighting and that it was questionable for incandescent lighting in general. In other ways,

such as suitability for engine-type construction, application to induction motors and synchronous converters and transmission of power to long distances, it met the needs of an ideal system, as then understood. Also, in parallel operation of engine-type alternators, which was one of the serious problems of those days, the 25-cycle machines were unquestionably superior to the 60-cycle ones, due to the lesser displacement of the e. m. f. waves with respect to each other with a given angular variation in the engine speeds. However, although the 25-cycle system presented so many advantages, it could not take care of the lighting business, and, therefore, could not entirely dominate the situation.

As regards 60 cycles, it was felt that this could handle the direct lighting situation in a very satisfactory manner and was possibly better suited for transformers than 25 cycles, although there were differences of opinion in this matter, especially when it came to the larger capacities. It was reasonably well adapted for induction motors in general, but not for very low speeds. In matters of transmission and in the operation of synchronous converters it was thought to be vitally defective.

From the above consideration it would appear that the 25-cycle systems presented the stronger showing as a whole and, therefore, there was a decided tendency toward this frequency, except in those cases where lighting directly from the alternating-current system was considered of prime importance. In those systems, such as many of the Edison companies, where low-voltage three-wire direct current was used from synchronous converters, the tendency was almost solidly toward the 25-cycle system. In those days the central station, which had gotten itself committed to the 60-cycle system so deeply that it could not change, was looked upon with commiseration. Sixty-cycle plants were looked upon, to a certain extent, as a necessary evil. In fact, so strong was the tendency toward 25 cycles that in many cases 25-cycle plants were installed for industrial purposes, where 60 cycles would have been better. The 25-cycle synchronous converter development advanced by leaps and bounds and the machines were so good in their operation that it was believed that 60-cycle converters could never be really competitive with them.

On the other hand, in those large plants, which were so "unfortunate" as to have 60 cycles installed, many apparent makeshifts were adopted to meet the various service requirements.

In arc lighting, incandescent lighting, transformers and motors there was no need for makeshifts. However, in conversion to direct current, one of the greatest difficulties appeared. There were many who advocated motor-generators for this purpose, largely because the 60-cycle converter was thought to be impracticable, in spite of the fact that the manufacturing companies were putting them on the market. The 60-cycle converter at that time bore a bad name. It is now recognized that many of the faults of the early 60-cycle synchronous converter operation were not in the converters themselves, but were, to a considerable extent, in the associated apparatus. Low-speed engine-type, 60-cycle generators were not always adapted for operation of synchronous converters. In fact, in numerous cases such generators would not operate in an entirely satisfactory manner in parallel with each other, and yet when it was attempted to operate synchronous converters from these same generators the unsatisfactory results were not blamed upon the generating system but upon defects of the converters themselves. Unfortunately, defects in the generating and transmission systems usually appeared in the converters as sparking and flashing, and such troubles naturally would be credited to defects in the construction of the converters themselves. In fact, in those days, 60-cycle converters were expected to do things which now are considered as absurd. For instance, in one case in the writer's knowledge a 60-cycle synchronous converter was criticized as being a very badly designed piece of apparatus, due to serious flashing at times. Investigation developed that this converter was expected to operate on either one of two independent 60-cycle systems with no rigid frequency relation to each other. The converter in service was thrown from one system to the other indiscriminately, and sometimes it flashed in the transfer and sometimes it did not. The machine was considered to be "no good" because it would not always stand such switching.

At one time the writer stood almost alone in his belief that the 60-cycle synchronous converter presented commercial possibilities sufficient to make it a strong future contender with the 25-cycle machine, provided proper supply conditions were furnished and certain difficulties in the proportions of the converter itself were overcome. One basis for his contention was that in some of the 60-cycle plants, where the generator rotation was quite uniform, the converters were evidently much superior in their operation to other plants, using slow-speed engine-type

generators with considerable periodic variations. In such plants the hunting tendency of the converters was very greatly reduced, with consequent improvement in sparking and general operation. It was early recognized that hunting was a very harmful condition, both in 60- and 25-cycle synchronous converters, but whereas it was a relatively rare condition in 25-cycle plants it was much more common with 60 cycles. However, the operating public was not particularly concerned whether the trouble was in the generating plant or in the converters themselves, as long as such trouble existed and was not overcome. Very early in the synchronous converter development it was found that hunting would produce sparking or flashing at the commutators of the converters. However, even in those plants where there was no hunting apparent, there was difficulty at times due to flashing, especially with sudden change of load, which resulted in temporary increase in the d-c. voltage. This was a difficulty which was inherent in the converter itself and could not be blamed entirely upon the generating or transmitting conditions, for 25-cycle machines were practically free from this trouble under similar conditions of operation. Investigation developed the fact that this flashing trouble was due largely to unduly high value of the maximum volts between commutator bars. This difficulty was recognized long before it was overcome, simply because certain physical limitations in construction had to be removed. There were two ways in which the maximum volts per bar could be reduced, namely, by increasing the number of commutator bars per pole and by decreasing the ratio of the maximum volts to the average volts per bar, that is, by increasing the ratio of the pole width to the pole pitch, but both of these involved structural limitations in the allowable peripheral speeds of the commutator and the armature core. Here is where a little elementary mathematics comes in. The peripheral speed of the commutator is directly proportional to the distance between adjacent neutral points on the commutator, and the frequency. Therefore, with a given frequency the distance between the adjacent neutral points is directly proportional to the peripheral speed. Thus, a commutator speed of 4500 ft. per min. which was then considered an upper limit, the distance between adjacent neutral points on a 60-cycle converter is only 7½ in. (19 cm.) This distance is thus fixed mathematically and is independent of the number of poles or revolutions per minute, or anything else, except the peripheral

speed and the frequency. With this distance of 7½ in., (19 cm), about the only choice in commutator bars per pole was 36, giving an average of 16⅔ volts per bar on a 600-volt machine, and nearly 20 volts per bar with momentary increase of voltage to 700, which is not uncommon in railway service.

However, it is not this average voltage which fixes the flashing conditions, but it is the maximum voltage between bars, and this is dependent upon the average voltage and upon the ratio of the pole width to the pole pitch. Here is where one of the serious difficulties came in. As mentioned above the pole pitch is directly dependent upon the peripheral speed of the armature core and the frequency. Therefore, in a 60-cycle machine, if the peripheral speed is fixed, the pole pitch is at once fixed. For example, with an armature peripheral speed of 7200 ft. per min., which was considered high at that time, the pole pitch becomes 12 in (30.48 cm.), regardless of any other considerations, and here was where a most serious difficulty was encountered. If a sufficiently wide neutral zone for commutation was allowed the interpolar space became so wide that there was not enough left for a good pole width. For instance, if the interpolar space was made 6 in. (15 24 cm.) wide, in order to give a sufficiently wide commutating zone to prevent sparking or flashing, due to fringing of the main field, then this left only 6 in. for the pole face. With this relatively narrow pole face the ratio of the maximum volts to the average volts was so high that with the 36 commutator bars per pole the machine was sensitive to arcing between commutator bars thus resulting in flashing. By widening the pole face this difficulty would be lessened or overcome but with the fixed pole pitch of 12 in. (30.48 cm.) the neutral zone would be so narrowed as to make the machine sensitive to sparking and flashing at the brushes. Thus, no matter which way we turned we encountered trouble. Obviously there were two directions of improvement, namely, by increasing the number of commutator bars, thus reducing the average voltage, and by increasing the pole pitch, thus allowing relatively wider poles with a given interpolar space. These two conditions look simple and easy, but it took several years of experience to attain them. When we have reached apparent physical limitations in a given construction, especially when such limitations are based upon long experience, we have to feel our way quite slowly toward higher limitations. For instance, in the case of the 60-cycle converters we could not boldly jump our

peripheral speeds 20 to 25 per cent higher and simply assume that everything was all right. We first had to build apparatus and try it out for a year or so. Troubles, due to peripheral speed, do not always become apparent at once, and thus time tests are necessary Therefore, while the peripheral speeds of the 60-cycle synchronous converters were actually increased 20 to 25 per cent practically in one jump, yet it took two or three years of experimentation and endurance tests before the manufacturers felt sure enough to adopt the higher speeds on a broad commercial scale. Thus, while the change from the older more sensitive type of 60-cycle converter to the later type occurred commercially within a comparatively short period yet the actual development covered a much longer period.

Let us see now what an increase of 25 per cent in the peripheral speeds actually meant. As regards the commutator, the number of bars could be increased 25 per cent, that is, from 36 to 45 per pole, which was comparable with ordinary d-c. generator practise. In the second place, an increase of 25 per cent in the peripheral speed of the armature core meant a 15-in. (38.1-cm.) pole pitch, where 12 in. (30.8 cm.) was used before. Assuming, as before, a 6-in. (15.24-cm.) interpolar space, then the pole face itself became 9 in. (22.8 cm.) in width instead of 6 in. (15.24 cm.) or an improvement of 50 per cent. In fact, this latter improvement was so great that some manufacturers did not consider it necessary to increase the number of commutator bars, although in the Westinghouse machines both steps were made.

The above improvements so modified the 60-cycle converter that it began to approach the 25-cycle machine in its general characteristics. It was still quite expensive compared with the 25-cycle, due to the large number of poles, and its efficiency was considerably lower than its 25-cycle competitor, on account of high iron and windage losses. However, due to the need for such a machine it was gradually making headway, in spite of handicaps in cost and efficiency.

Almost coincident with the initiation of the above improvements in the 60-cycle converter, came another factor which has had much to do with the success of this type of machine. This was the advent of the turbo-generator for general service. As stated before, one of the handicaps of the 60-cycle converter was in the non-uniform rotation of the engine type generators which were common in the period from 1897 to about 1903 or 1904. But, about this latter date, the turbo-generator was making

considerable inroads on the engine-type field and within a relatively short period it so superseded the former type of unit, that it was recognized as the coming standard for large alternating power service. With the turbo-generator came uniform rotation and this at once removed one of the operating difficulties of the 60-cycle converters. However, in the early days of the turbo-generator, 25 cycles still was in the lead and many of the earlier generators were made for this frequency, especially in the larger units. But it was not long before it was recognized that 60 cycles presented considerable advantage in turbo-generator design due to the higher permissible speeds. In the earlier days of turbo-generator work, this was not recognized to any extent, as the speeds of all units were so low that the effect of any speed limitations was not yet encountered. For instance, a 1500-kw , 60-cycle turbo-generator would be made with six poles for 1200 revolutions, while a corresponding 25 cycle unit would be made with two poles for 1500 revolutions. This slightly higher speed at 25 cycles about counterbalanced the difficulties of the two-pole construction compared with the six-pole. However, before long, more experience enabled the six pole, 60-cycle machine to be replaced at 1800 revolutions, and a little later by two poles at 3600 revolutions. This, of course, turned the scales very much in the other direction. In larger units, however, the advantage still appeared to be in favor of 25 cycles, but in the course of development, 1500 revolutions was adopted quite generally for 25-cycle work, and this was the limiting speed, as such machines had only two poles, or the smallest number possible with ordinary constructions. On the other hand, for 60 cycles, 1800 revolutions was adopted quite generally for units up to almost the extreme capacities that had been considered, consequently the constructional conditions in the large machines swung in favor of 60 cycles. Therefore, with the coming of the steam turbine and the development of high-speed turbo-generator units, the tendency has been strongly toward 60 cycles. This, with the greater perfection of the 60-cycle converter, had much to do with directing the practise away from the 25 cycles.

However, there were other conditions which tended strongly toward 60 cycles. In the early development of the induction motor, the 25-cycle machines were considerably better than the 60-cycle and possibly little or no more expensive. However, as refinements in design and practise came in, certain important advantages of the 60-cycle began to crop out. For instance,

with 25 cycles there is but little choice in speed, for small and moderate size motors. At this frequency a four-pole motor has a synchronous speed of only 750. The only higher speed permissible is 1500 revolutions with two poles, and it so happens that in induction motors the two-pole construction is not materially cheaper than the four pole, consequently the principal advantage in going to 1500 revolutions was only in getting a higher speed where such was necessary for other reasons than first cost. However, in 60 cycles the case is quite different, where a four-pole machine can have a speed of 1800 revolutions, synchronous, a six pole 1200, an eight pole 900 and a ten pole 720 revolutions. In other words, there are four suitable speed combinations where a 25 cycle motor had only one. Moreover, with the advance in design it developed that these higher speed 60-cycle motors could be made with nearly as good performances as with the 25-cycle motors of same capacity, and at somewhat less cost. However, leaving out the question of cost, the wider choice of speeds alone would be enough to give the 60-cycle motor a pronounced preference for general service.

However, there is one exception to the above. Where very low-speed motors are required, such as 100 rev. per min., the 60-cycle induction motor is at a considerable disadvantage compared with 25 cycles, or this has been the case in the past. It is partly for this reason that the steel mill industry, through its electrical engineers, adopted 25 cycles as standard some ten or fifteen years ago. At that time, it was considered that in mill work, in general, there would be need for very low-speed motors in very many cases. However, due to first cost, as well as other things, there has been a tendency toward much higher speeds in steel mill work, through the use of gears and otherwise, so that part of this argument has been lost. However, there still remain certain classes of work where direct connected very low-speed induction motors are desirable and where 25 cycles would appear to have a distinct advantage.

In view of the above considerations, steel mill work has heretofore gone very largely toward 25 cycles, particularly where the mills installed their own power plants. However, in recent years there has been a pronounced tendency toward purchase of power, by steel mills, from central stations, and the previously described tendency of central stations toward 60 cycles has forced the situation somewhat in the steel mills, particularly in those cases where the central power supply company can furnish

power at more reasonable rates than the steel mill can produce in its own plant. This, therefore, has meant a tendency toward 60 cycles in steel mill work, even with the handicap of inferior low-speed induction motors. But, on the other hand, remedies have been brought forward even for this condition. The great difficulty in the construction of low-speed, 60-cycle induction motors is in the very large size and cost if constructed for normal power factors, or the very low power factor and poor performance if constructed of dimensions and costs comparable with 25 cycles. In the latter case the extra cost is not entirely eliminated because a low power factor of the primary input implies additional generating capacity, or some means for correcting power factor on the primary system. However, in some cases it is entirely practicable to correct the power factor in the motors themselves by the use of so called "phase advancers" of either the Leblanc or the Kapp type. Such phase advancers are machines connected in the secondary circuits of induction motors and so arranged as to furnish the necessary magnetizing current to the rotor or secondary instead of to the primary In this way the primary current to the motor will represent largely energy and the power factors can be made equal to, or even much better than in, the corresponding 25-cycle motor; or, in some cases, the conditions may be carried even further so that the motor is purposely designed with a relatively poor power factor, in order to further reduce the size and cost, and the phase advancers are made correspondingly larger. In those cases where the cost of the phase advancer is relatively small compared with the main motor, there may be a considerable saving in the cost of the main motor and then adding part of the saving to the cost of the phase advancer.

One difficulty in the use of phase advancers is found in the variable speeds required in some kinds of mill work. In those cases where flywheels driven by the main motors are desirable to take up violent fluctuations in load, it is necessary to have considerable variations in the speed of the induction motor, in order to bring the stored energy of the flywheel into play. Unfortunately this variable speed in the induction motor is one of the most difficult conditions to take care of with a phase advancer, so that here is a condition where the 60-cycle motor is at a decided disadvantage.

Thus it may be seen from the above that even in the steel mill field, where the induction motor has the most extreme applications, there is quite a strong tendency toward 60 cycles, due to the purchase of power from central supply systems.

There remains one more important element which has had something to do with the tendency toward 60 cycles, namely, the transmission problem. In the earlier days of transmission of alternating current, 25 cycles was considered very superior to 60 cycles due to the better inherent voltage regulation conditions. At one time, it was thought that 60 cycles had a very limited field for transmission work. However, a number of power companies in the far west had installed 60-cycle plants, principally for local service and with the growth of these plants came the necessity for increased distance of transmission through development of water powers. At first it was thought they were badly handicapped by the frequency, but gradually the apparent disadvantages of their systems were overcome and the distances of transmission were extended until it became apparent that they could accomplish practically the same results as with 25 cycles. Part of this result has been obtained by the use of regulating synchronous condensers. It is a curious fact that the possibility of synchronous motors used as condensers for correction of disturbances on transmission systems, has been known for about 25 years, but it is only within quite recent years that they have come into general use as a solution of the transmission problem, and largely in connection with 60-cycle plants. In 1893 the writer applied for a patent on the use of synchronous motors as condensers for controlling the voltage at any point on a transmission system by means of leading or lagging currents in the condenser itself. A broad patent was obtained, but there was no particular use made of it until it had practically expired.

Another improvement came along which still further helped to advance 60 cycles to its present position, namely, the use of commutating poles in synchronous converters. The principal value of commutating poles in the 60-cycle converters, has not been so much in an improvement in commutation over the older types of machines, as in allowing a very considerable reduction in the number of poles with corresponding increase in speed, resulting in reduction in dimensions. As a direct result of this increase in speed the efficiencies of the converters have been increased. If, for instance, the speed of a given 60-cycle converter can be doubled by cutting its number of poles to one-half, while keeping the same pole pitch and the same limiting peripheral speed, then obviously the amount of iron in the armature core is practically halved and, at the same magnetic densities the iron loss is also practically halved. Also with the same

peripheral speed and half diameter of armature the windage losses can be decreased materially. Thus the two principal losses in the older converters have been very much reduced. There have also been reductions in the total watts for field excitation, and in other parts, so that, as a whole, the efficiency for a given capacity 60-cycle converter has been brought up quite close to that of the corresponding 25-cycle machine, even when the latter is equipped with commutating poles. This gain of the higher frequency compared with the lower is due to the fact that the lower-frequency machine was much more handicapped in its possibilities of speed increase, and furthermore, the iron losses and windage represented a much smaller proportion of the total losses in the low-frequency machine. This improvement in the efficiency of the 60-cycle converter together with the lower losses in the 60-cycle transformer as compared with the 25-cycle, has brought the 60-cycle equipment almost up to the 25-cycle, so that the difference at present is not of controlling importance. This development has given further impetus toward the acceptance of 60 cycles as a general system.

Formerly a serious competitor with the 60 cycle converter was the 60-cycle motor-generator. This was installed in many cases because it was considered more reliable and more flexible in operation than the synchronous converter. Both of these claims were true to a certain extent. However, with improvements in the synchronous coverter the difference in reliability practically disappeared, but there remained the difference in flexibility. In the motor-generator set, the d-c. voltage could be varied over quite a wide range, while in the older 60-cycle rotaries the d-c. voltage held a rigid relation to the alternating supply voltage. However, with the development and perfection of the synchronous booster type of converter, flexibility in voltage was obtained with relatively small increase in cost and minor loss in economy. This has been the last big step in putting the 60-cycle converter at the front as a conversion apparatus, so that today it stands as the cheapest and most economical method of converting alternating current to direct current. Moreover, while the 25-cycle synchronous converter has apparently reached about its upper limit in speed, there are still possibilities left for the 60-cycle converter.

In line with the above it is of interest to note that for units of 1000 kw. and less, the 60-cycle converter has nearly driven the 25-cycle out of business from the manufacturing standpoint.

For the very large size converters, 25 cycles still has the call, but largely in connection with many of the railway and three-wire systems, which have been installed for many years; that is, the growth of this business is in connection with existing generating systems. However, the 60-cycle converter, in large capacity units, is gaining ground rapidly and it is of interest to note that the largest converters yet built, namely, 5800 kw., are of the 60-cycle type.

One most interesting point may be brought out in connection with the above described "battle of the frequencies", namely, it was fought out in the operating field, and between conditions of service, and not between the manufacturing companies. This is a very good example of how such matters should be handled. Here the engineers of the manufacturing companies were expending their efforts to get all possible out of both frequencies, and consequently development proceeded apace. When 60-cycle frequency seemed to be overshadowed by its 25-cycle competitor, the engineers took a lesson from the latter and proceeded to overcome the shortcomings of the former. It was no innate preference of the designing engineers that has brought the higher frequency to the fore; it was the recognition that it had greater merits as a general system, if its weak points could be sufficiently strengthened; and, therefore, the engineers turned their best efforts toward accomplishing this result.

It must not be assumed, for a moment even, that because 60 cycles appears to be the future frequency in this country, that 25 cycles was a mistake. Decidedly it was not. In reality it formed a most important step toward the present high development of the electric industry Many things we are now accomplishing with 60 cycles would possibly never have been brought to present perfection, if the success of the corresponding 25-cycle apparatus had not pointed the way. The success of the 25-cycle converter, and the high standard of operation attained, gave ground for belief that practically equal results were obtainable with 60 cycles. Therefore, the 25-cycle frequency served a vast purpose in electrical development; it was a high class pacemaker, and it isn't entirely out-distanced yet.

There has been considerable speculation as to what two standard frequencies would have met the needs of the service in the best manner, and would have resulted in the greatest development in the end. It has been claimed by some, that 50 and 25 cycles would have been better than 60 and 25. In the earlier

days possibly the former would have been better, but as a result both standards might have persisted longer. In any case, the general advantages would have been small. In one class of machines, namely, frequency changers, consisting of two alternators coupled together, the 25-50 combination would certainly have been advantageous.

Again it has been questioned whether 30 and 60 cycles would not have been a better choice. This was the original Westinghouse choice of frequencies, but not on account of frequency changers. As stated before, it was felt that 30 cycles could do about all that 25 cycles could, and would give an advantage of 25 per cent higher speed in motors and converters, with correspondingly higher capacities. Also for direct coupled alternators, the two-to-one ratio of frequencies would fit in nicely with engine speeds, in most cases. Possibly, from the present viewpoint, the choice of thirty cycles, would have longer retained the double standard.

Something further may be said regarding the 40-cycle system, brought out by the General Electric Company. This contained many very good features, for the time it was brought out. It was then believed that if the 60 cycle frequency was retained, the double standard was necessary. The 40-cycle system was an attempt to eliminate this double standard. It apparently furnished a better solution than 60 cycles then promised for the synchronous converter problem, and was a fair compromise in about everything else. But it came too late, for the 25-cycle system was too firmly entrenched, and for further development, the designing engineers preferred to expend their energies in seeing what could be accomplished with 60 cycles, as this seemed to present greater possibilities than either 25 or 40, if it could be sufficiently perfected. Thus the 40-cycle system probably missed success due to being just a little too late.

As to 50 cycles, it was stated that this is still in use to a limited extent. Most of the 50-cycle plants in this country are in California. Such plants were started during the nebulous period of the frequencies, and have persisted, to a certain extent, partly because certain 60-cycle apparatus could be easily modified to meet the 50-cycle requirements. Also, as 50 cycles is the standard in many foreign countries to which this country exports equipment, the use of 50 cycles in some home plants has not been unduly burdensome from the manufacturers' standpoint.

In addition to the preceding, there have been certain classes

of electric service which have depended upon frequency, but which have not been a determining factor in fixing any particular frequency. Among these may be considered commutating types of a-c. apparatus. The first a-c. commutating motors of any importance, which appeared, were, of course, the 25-cycle, single-phase railway motors. These as a rule have operated from their own generating plants, or from other plants through frequency-converting machinery. One exception in the railway work may be noted in the use of 15 cycles on the Visalia plant in California. There is a pretty well defined opinion among certain engineers experienced in such apparatus that some low frequency, such as 15 cycles, would present very considerable advantages in the use of single-phase railway motors in very heavy service, such as on some of the western mountain roads. Here the problem is to get the largest possible motor capacity on a given locomotive, and the main advantage of the lower frequency would be in allowing a very materially higher capacity within a given space. This does not imply reduced weight or cost compared with the 25 cycles, but simply means greater motor capacity. With the modern, more highly developed, single-phase types of railway motors, it would appear that there may be very considerable possibilities in 15 cycles.

Outside of the railway field, there has been more recently a development of various types of a-c. commutating apparatus, principally in connection with heavy steel mill electrification work. Such apparatus has been largely in the form of three phase commutating machines and these have been used principally in connection with speed control of large induction motors. As these regulating machines are usually connected in the secondary circuits of induction motors, the frequency supplied is represented by the slip frequency. Consequently where the slip frequency never rises to a large percentage of that of the primary system, such commutating motors are applicable without undue difficulties. Such motors, presumably are better adapted for 25-cycle mill equipments than for 60-cycle, but due to the tendency, already described, for steel mills to go to 60 cycles on purchased power, it has been necessary to build these three-phase commutating motors for the regulation of 60-cycle main motors, in many cases.

There is still another class of service, which has come in recently, where the choice of frequency is of much importance, but where there is no great necessity for adhering to any standard,

namely, in heavy ship propulsion by electric motors. As each ship equipment is a complete system in itself, and as it cannot tie up with other systems, there is not any controlling need for maintaining any definite frequency or voltage. Except in similar vessels, there is little chance for duplication in parts, as the various equipments vary so much in size and capacity. In consequence it has been found advisable, at least up to the present time, to design each propulsion equipment for that frequency which best suits the generator and motor speeds, taking into account the various operating conditions and limitations, such as the different running speeds, steaming radius, etc. In consequence, different maufacturers bidding on such equipments may specify different frequencies, depending upon the constructional features of their particular types of apparatus. At the present time with the relatively small amount of experience obtained with the electrical propulsion of ships, it looks as if it would be a considerable handicap to attempt to adopt some standard frequency for all service. Later, with wide experience, it may be possible to adopt some compromise frequency, which will not unduly handicap any of the service.

Conclusion

It has been the writer's intention to show that, as a rule, the choice of frequency has been a matter of most serious consideration, based upon service conditions at the time. Moreover, in view of the wide range of conditions encountered, it is surprising how few frequencies have been seriously considered in this country. Occasion has arisen, times without number, where an obvious solution of a given problem would lie in modification of the frequency to allow the use of apparatus and equipment already designed, but the engineers of the manufacturing organization have steadily held out against such policy, regardless of the apparent need of the moment. The swing of the pendulum from 60 cycles to 25 cycles and back, has covered a period of many years and, therefore, cannot be considered as a fad of the moment, but is the result of well defined tendencies, backed by the best engineering experience available. As a rule no manufacturer has made any particular frequency his "pet," but all have worked to develop each system to its utmost.

THE DEVELOPMENT OF THE ALTERNATING-CURRENT GENERATOR IN AMERICA

FOREWORD—The following article, which first appeared in the Electric Journal, contains a fairly complete brief history of the evolution of the alternating-current generator in so far as the Company, with which the writer is connected, is concerned. Reference is made incidentally to the work of other manufacturing companies, but this is not very complete, as the writer did not have the necessary material available for describing such developments, except in a very general way.—(ED.)

IN the early days of the alternating-current generator, it was constructed in almost as many types as there were designers. The principal endeavor of each designer appeared to be toward the development of a new alternator which would bear his name. A few of these early types were of the rotating field construction, while a much greater number were of the rotating armature type. Some had iron core armatures, while others had coreless armatures, and there were many discussions as to whether the core or the coreless type was superior and would survive. Many of the early predictions would now form quite interesting reading, in view of the fact that present practice is so far removed from the early anticipations. Here and there among the early machines was one which contained some of the important elements of recent apparatus, but in many cases such machines disappeared in the general course of development, the meritorious features being insufficient to save the type.

SURFACE WOUND ARMATURES

In America, the principal early type of alternator had a rotating armature with surface windings and an external cast iron multipolar field. This type was used very considerably or, in fact, almost exclusively, from 1886 to 1890. This was the type built by the Westinghouse and the Thomson-Houston Companies. There were only minor differences in the construction of the machines built by these two companies which, however, at that time, appeared to be very great. These differences consisted principally in the way the end windings of the armature coils were supported, in the construction of the end bells and ventilating openings in the armature core, in the method of attaching the armature core to the

shaft, in the winding of the field coils in metal bobbins, etc. Both machines had surface windings with concentric coils, one layer deep in the radial direction. In the Westinghouse construction, the end windings were turned down toward the shaft and were supported by radial wooden clamps, as indicated in Fig. 1. In the Thomson-Houston armature, the end windings were arranged in an axial instead of a radial direction, and were supported by bands or external clamps. This construction is also indicated in Fig. 1. The Slattery machine, which was also on the market at that time, was of the same general type as the above machines. Presumably these two different methods of end winding were used on account of the patent situation. At that time there was much discussion of the respective merits of the two constructions.

These early machines were built principally for frequencies of 15,000 and 16,000 alternations per minute (125 and 133 cycles per second). In those days, everything was rated in alternations per minute, as this represented the product of the number of poles by the number of revolutions. Such high frequencies were selected, mainly, on account of transformer conditions, and not alternator design. Practically all alternating service consisted of house to house lighting, and in relatively small units, and the higher frequency was supposed to be of great advantage in transformer design and operation, which presumably was the case with the very small amount of data and experience available at that time.

About the only commercial voltage for alternating work at that time was 1000 or 1100 volts. This was supposed to be excessively high and dangerous, and there was much question whether such an excessive voltage should be permitted. This matter was actually taken before a number of the state legislatures for the purpose of obtaining laws prohibiting or limiting the use of such voltage. Another reason why no higher voltage was used was in the construction of the alternators and transformers. With the experience and materials available at that time, together with the high speed rotating armature construction and the surface windings, even 1100 volts was a very serious problem in the generator. About 1889 or 1890, there appeared some slight demand for higher voltages, and a few 2000 or 2200 volt surface-wound alternators, of the then standard type, were built. However, even then it was recognized that the surface-wound type of alternator was not well adapted for higher voltages, and there was much question whether a different type winding should not be developed

for 1100 volts. This gradually led to the next big step, namely, the development of the "toothed" type of alternator with one big tooth per pole, in distinction from the slotted type of armature with a number of slots per pole, which was a considerably later development.

Toothed Armatures

The first commercial toothed type of armature appears to have been gotten out by the Westinghouse Company. These first ma-

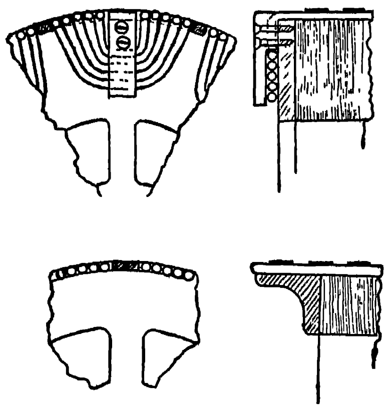


FIG. 1—SURFACE WOUND ARMATURE WITH RADIAL CLAMPS (UPPER) AND WITH AXIAL CLAMPS (LOWER)

chines were radically different, in details of construction, from the later toothed armature types of machines which came into general use. The first toothed armatures were small air-gap machines. In the surface-wound armatures, the clearance between the armature surface and the field poles was comparatively small, although the total air-gap (iron to iron) was large on account of the surface winding. In constructing the new toothed armature, the actual clearance (iron to iron) between armature and field was kept about the same as in the surface-wound alternators (bands to iron), but this clearance actually represented the total air-gap in the toothed type. Moreover, in sinking the windings below the surface, it was endeavored to maintain a practically uniform outside surface, so that overhanging tooth tips were used with relatively narrow slots for putting in the windings. The general construction was similar to Fig. 2. On account of the small clearance, and consequent higher magnetic conditions, it was found necessary to use lamin-

ated poles with these machines in order to avoid excessive field heating.

The self-induction of the armature windings on these machines was very high compared with the old surface-wound armatures and therefore, in order to obtain passably good regulation, fewer armature turns had to be used, with correspondingly higher inductions, and this made the use of solid poles impracticable on account of heating. Furthermore, on account of the overhanging tooth

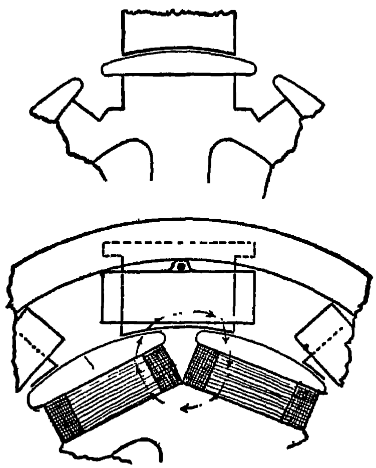


FIG 2.

tips, the small air-gap and the high induction per pole, this early type of toothed armature was very noisy. In one instance, it was credibly reported that one of these machines could be heard two miles away on a quiet night. However, several machines of this construction were put out by the Westinghouse Company, and operated for many years.

Meanwhile, the possibilities of the toothed armature construction in the old cast iron field were being given consideration. The writer made a special study of this matter, and finally decided that, in order to make this construction possible with solid cast iron poles, it would be necessary to work at relatively low inductions per pole, and with a very large air-gap, (fully as large as on the old surface-wound machines) and with a shape of tooth tip which did not have such great width compared with the pole tip as shown in Fig. 2. This meant that a pole tip and air-gap as shown in Fig. 3, should be used. With this arrangement, the armature

self-induction would still be relatively high, and the regulation correspondingly bad, necessitating some form of compounding for regulating the voltage, similar to the compounding of a direct-current generator. This armature construction was worked out in detail for a 37.5 kilowatt field (that is, for the standard field of the 37.5 kw surface-wound type of machine). The armature teeth

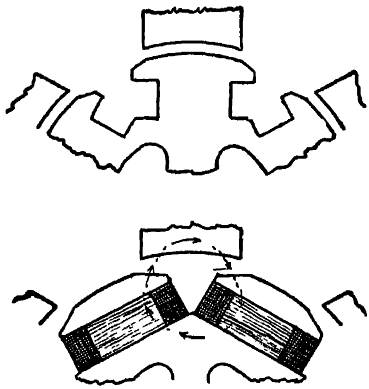


FIG. 3

were similar to those in Fig. 3, in shape, and the air-gap or clearance from iron to iron, was made ⅜ inch on each side of the machine. The field was also compounded. When this machine was put on test, it was found at once that it could be loaded to 60 kilowatts without undue heating of the armature and field iron, and the problem of perfecting this machine then became one merely of increasing the amount of armature copper to carry the current at the 60 kilowatt rating. This, therefore, represented a big step in the development of the American type alternator. It was found that all the other Westinghouse standard cast iron machines of the rotating armature type could readily be changed in line with the above improvement.

Compounding Alternators

The compounding of the 60 kilowatt machine was not a new feature, for already some of the laminated field toothed-armature type of machines had been compounded, in order to improve their regulation. Two different methods of compounding alternators had been developed by the Westinghouse and Thomson-Houston Companies, respectively. In the Westinghouse armature construc-

tion, the armature discs were punched in single pieces, with spokes, and were threaded directly on the armature shaft, no spider being used. This construction is illustrated in Fig. 4. In the assembled armature, the spokes were therefore of laminated material. These laminated spokes were utilized as the core of a compounding transformer. One lead from the armature winding was carried around the spokes of the armature before passing to the collector ring. This winding formed the primary of a series transformer. The secondary was also wound on the spokes, and the two ends were carried to the bars of a rectifying commutator on the shaft. The number of commutator bars was equal to the number of poles. The alternating current from the secondary winding was by this means changed to a pulsating direct current.

In the Thomson-Houston method of compounding, the main armature current was carried directly to a rectifying commutator, and, after being commutated, was passed to the field-compound winding, and back to the commutator, and then to a collector ring.

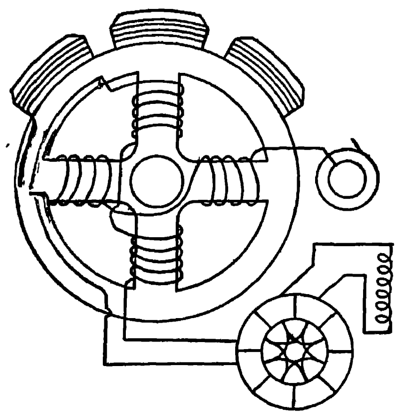


FIG. 4—SKETCH OF COMPENSATED TYPE OF WINDING

The main armature current therefore passed directly through the field, while in the Westinghouse method the secondary current from a series transformer was passed through the field. Both methods represented series compounding, and gave practically equal results, but there was much discussion as to the merits of the two methods. Both of these methods delivered pulsating direct current to the field winding. There was considerable inductive e. m. f. set up in the field windings by this pulsation, and this tended to cause inductive discharges across the rectifying com-

mutators. In the Thomson-Houston method this trouble was overcome to a considerable extent by the use of a non-inductive shunt in parallel with the rectifying commutator, i.e., across the compound winding. In the Westinghouse method a similar result was accomplished by saturating the series transformer (or armature spokes) to such a high point that the inductive kick from the field could readily discharge through the secondary winding of the transformer without giving high enough voltage to flash across the commutator.

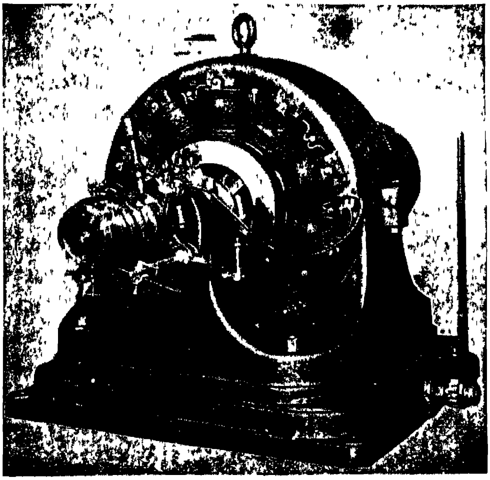


FIG. 5—EARLY WESTINGHOUSE 60 KILOWATT ALTERNATOR WITH COMPENSATING WINDING

The details of this method of compounding have been gone into rather fully, as this compounding was, at that time, an important step in our progress. The fact that of all these machines were built for single phase, allowed us to use such compounding. With the advent of polyphase generators, such methods of compounding soon disappeared, principally for the reason that a great majority of the early polyphase machines handled separate single-phase loads on the different phases, and it was not practicable to compound for these independently.

The above toothed type generator came into use about 1890 and lasted for several years, or practically until polyphase generators actually came into fairly general use before true polyphase loads became common. These toothed type generators allowed

the use of relatively high voltages, as far as the armature winding was concerned, so that 2200 volts became comparatively common, and even 3300 volts or higher was used in some cases. In fact, the limit in such machines appeared to be at the collector rings, rather than in the armature winding.

Something may be said regarding the type of winding used on the armatures of these machines. In the Westinghouse construction the armature coils were machine-wound and taped before placing on the armature core. Each coil was made wide enough to slip over the top of the armature tooth, as shown in Figs. 6 and 7. This made the coil considerably wider than the body of the armature tooth, so that, after slipping over the tooth top the coil had to be reduced in width by special clamping tools. Supporting wedges were then driven in between adjacent coils.

Something may be said regarding the temperatures of these early alternators, both of the surface-wound and of the toothed types. In those days temperature measurements were very crude compared with present practice, which is admittedly still only approximate. In some of the surface-wound armatures excessively high temperatures must have been encountered in many instances, judging from the appearance of the insulation on the individual wires, after a year's service, for instance. However,

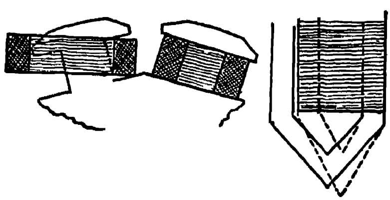


FIG. 6—SKETCH SHOWING METHOD OF PUTTING MACHINE WOUND COILS ON THE POLES

it was difficult to obtain reasonably correct temperature of the armature windings, for the actual temperature of the conductors was undoubtedly reduced very greatly before the armature could be brought to a standstill. Even after this, temperature rises of 50 or 60 degrees C. were not considered as excessively high. Without doubt, some of these early machines, at times, attained actual internal temperatures of 120 to 130 degrees C., or even higher, with insulation on the conductors consisting of untreaded cotton fibre. No overloads were possible, for each size of machine was rated in as many "lights" as it could carry on a shop test without

breaking down. The first few minutes, while starting up a new alternator in the testing room, were always anxious ones for the operators, especially so if any "improvements" had been made on the armature winding. Any defect in winding, or wrong connection usually resulted in a stripped armature and much flying copper. If nothing happened within the first few minutes after the machine was put on load, the attendants all came out from behind posts and other protections and went on with their work.

When the toothed armature came into use the above conditions were much alleviated. Defects in construction, or short-circuits, could not strip such armatures, and thus the danger and excitement were removed. However, it was found that the first short run did not tell the story of excessive heating as promptly as in the case of the surface-wound type. Experience showed that the toothed construction apparently could stand a severe shop test and still go wrong under similar loading within a short time after being installed. It was found that a given size of conductor would not carry as much current in the concentrated coils of the toothed construction as was the case in surface-wound coils. However, the method of testing the temperature did not show this, as the main part of the toothed armature coil was so embedded and so covered with insulation that the thermometer readings did not indicate nearly the true temperatures. The size of wire and the amount of copper in the coils then had to be increased until the machines did stand up in service. The true explanation of the discrepancies was not well understood at that time. In these toothed alternators, as in the surface-wound machines, the first machines were rated in "lights," but gradually the kilowatt rating came into use and became standard practice.

INTRODUCTION OF POLYPHASE ALTERNATORS

In 1892 and 1893, polyphase alternators began to be considered seriously. In 1889 and 1890, a few such alternators had been built for the operation of Tesla induction motors. These early polyphase alternators were of the surface-wound, rotating armature type. These machines were very special in construction, and, like the Tesla motors, did not find much of a market. However, in 1892 and 1893, it began to be recognized that the best way to encourage the development of the induction motor would be by creating a demand for it, and it was decided that a good way to create a demand would be by encouraging the general adoption of

polyphase alternators and supply circuits, with the idea that, when a suitable supply circuit was available, there was eventually bound to be a demand for motors to operate upon such circuits. With this general policy in view, there was great activity in the development of polyphase generators. This very quickly led to a very considerable departure in armature construction from the usual toothed armature as used in single-phase machines. The polyphase winding, requiring two or more coils per pole, naturally

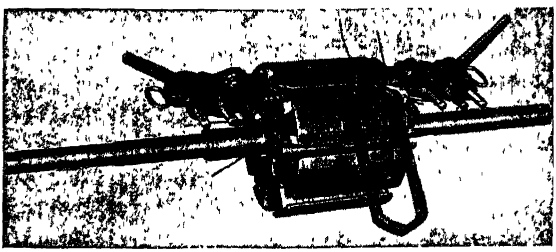


FIG. 7—VIEW OF ARMATURE IN PROCESS OF PLACING COILS AND CLAMPING THEM INTO SHAPE IN THE SLOTS

tended toward the slotted armature construction with two or more slots per pole. It was soon recognized that, in general, the larger the number of slots per pole and the smaller the number of conductors per slot, the better would be the general characteristics of the machine, so that the construction naturally tended toward the modern slotted type. Moreover, practically all the development in polyphase alternators was at relatively low frequency, compared with former practice. It so happened that there had been a well-defined tendency toward lower frequency in the period from 1890 to 1892. This tendency was largely independent of the induction motor problem for, at the time it became most pronounced, there was no true induction motor problem. It was becoming recognized that 125 to 133 cycles per second was too high for certain classes of work and for engine type generators, and that, in general, a very considerably lower frequency must eventually be adopted. A great many lower frequencies were tried by the different manufacturing companies, ranging from 50 to 85 cycles. However, 60 cycles seemed to have the preference at the time polyphase alternators began to come in.

The early polyphase generators were mostly of the rotating armature type, and usually with a fairly large number of slots per

pole. One notable exception was the "monocycle" machine which usually had only two slots per pole, one large slot for the main armature winding, and one smaller slot for the so-called "teaser" winding. Also, the early two-phase alternators of the "inductor" type, built by the Stanley-Kelly Company, frequently had only two slots per pole. However, it may be said that, from 1893 to about 1898, the great majority of the American built alternators were of the rotating armature type with distributed armature windings. The principal exceptions were the Stanley inductor type of machines and a few special "rotating field" machines, as distinguished from the inductor type.

The rotating armature machines were usually of 1100 or 2200 volts, although a few of considerably higher voltage were constructed. A few cases may be cited where special constructions were used. For instance, the principal lighting plant at the Chicago World's Fair in 1893, consisted of a large number of Westinghouse "twin" type generators. Each unit had two single-phase, standard toothed type armatures side by side on the same shaft. The teeth of the two armatures were staggered 90 electrical degrees with respect to each other, so that the two together could deliver currents having 90 degrees relation to each other. The object of this construction was to obtain polyphase current with standard single-phase types of machines without any radically new development. This type of unit did not persist and, in fact, was simply an expedient for this particular occasion.

The First Niagara Generators

Also, in 1892 and 1893, the first large Niagara electrical development was worked out. The advisory engineers of this plant proposed 5000 horse-power generators, having stationary internal armatures and rotating external fields to obtain large flywheel capacity. In fact, the construction was not unlike the usual rotating armature machine of that period, as far as general appearance of the armature and field cores and windings were concerned. However, the method of supporting and rotating the heavy external field at a speed which, at that time, was considered excessively high, required an "umbrella" type of field support, which gave these machines a distinctive appearance. This type of construction did not persist, although these early machines are still in operation.

A further distinctive feature in these first Niagara machines was in the frequency employed. A speed of 250 revolutions per minute was decided upon. The engineers of the power company proposed eight-pole machines, giving 2000 alternations per minute or 16 2-3 cycles per second. The Westinghouse Company proposed, as an alternative, 16 poles, giving 33 1-3 cycles, the advantages claimed for this frequency being that it was better suited for motors and rotary converters, which were then promising to become of importance. One advantage claimed for the 16 2-3 cycle machine was that it would permit the use of commutator type alternating-current motors. After much discussion, and weighing and balancing of all the various arguments for and against these two frequencies, it was finally decided to use 12 poles, giving 3000 alternations per minute, or 25 cycle polyphase current and, as far as the writer knows, this was the origin of the present 25 cycle standard.

Considering what a radical departure from ordinary construction was made in these first Niagara generators, it is self-evident that many curious and interesting conditions developed during their design, construction and tests. As far as the writer knows, these were the first large alternators which were deliberately short-circuited at their terminals when running at full speed and at normal field charge. There were no instruments available to measure the first current rush, but it was obvious that this current was far greater than the steady short-circuited current of the machine under similar field charge, for there were ample evidences of a terrible shock at the moment of short-circuit. It was suspected at that time that the first rush of current was only limited by the armature impedance, and not by the so-called synchronous impedance which fixes the value of the steady short-circuit current.

This also was the earliest machine of which the writer predetermined the field form and wave form by analysis of the flux distribution. Later, when making shop tests on one of these machines, the e. m. f. wave form was measured directly by rotating the field at normal field charge at such an extremely low speed that a voltmeter connected across the armature terminals showed such gradual variations in e. m. f. that readings taken at regular intervals could be plotted to form the voltage wave. Slow rotation was obtained by means of a steel cable wrapped about the outside of the external field and with one end of the cable attached to a small diameter spindle around which it was wrapped at a very

slow rate. This was a very crude method, but the wave form thus obtained checked very accurately with tests made some years later.

Also, the early Niagara machines embodied one of the first distinct attempts to ventilate alternators artificially. Early belted machines had had small ventilating bells on each end. But these Niagara machines were designed primarily with a view to setting up an abnormal air circulation by means of special "scoops" or ventilators on the umbrella supports. Very much thought and discussion were given to this subject of artificial ventilation. The results of our tests led to the arrangement of the scoops so that they acted as exhaust pipes.

Also, water cooling of the armature spider was tried on some of these early machines, but proved ineffective, due to the fact that the cooling medium was applied too far away from the point of development of the larger part of the armature iron and copper losses.

Influence of Direct-Current Design

It must be kept in mind that the general trend of direct-current development had a certain influence on alternating-current generator work. For example, there had been a slow, but positive tendency in direct-current generators, toward the engine type construction. Also, from 1890 to 1893, direct-current generator armature construction had changed from the surface wound to the slotted type. This doubtless had some influence in changing alternator design toward the slotted type, especially when the polyphase type of windings came into use. Also, there was a pronounced tendency toward the engine type, slow speed alternator, accompanying direct-current practice. Practically all of these early engine type alternators, except the inductor type, had rotating armatures. Meanwhile, an interesting development took place in the armature construction of some of these machines. In most of the smaller belted machines, open armature slots were used with machine-wound armature coils. However, many of the early larger machines, especially of the engine type, were built for relatively low voltage, such as 440 volts, two or three phase. This admitted in many cases of simple bar windings with one or two conductors per slot. This allowed partially closed armature slots with shoved-through straight conductors, and bolted-on end windings, giving a very strong substantial type of winding for resisting the rotational stresses. The partially closed slot became a

sort of standard in Westinghouse machines, and endured for a number of years, and was even carried into the stationary armature type of machine when rotating fields came into general use. This partially closed slot arrangement was a very good one as long as the generator voltages were relatively low. The same may be said of the rotating type of armature as a whole. However, when high voltages came into more general use, a different construction was preferable.

In reviewing the period of the rotating armature, slotted types of machines, the monocyclic system should be briefly described. Apparently this was gotten out with the idea that it avoided the patented features of the Tesla polyphase system. The armature circuits on this monocyclic system were so arranged that, when carrying load, one phase carried nearly all of the energy load, while both phases supplied magnetizing current for the operation of induction motors. During the period when this machine was in vogue, single-phase lighting work represented the principal service, while induction motor loads were relatively small. With increased use of polyphase loads, and with the elimination of the patent situation, the monocyclic system gradually dropped out.

It was early recognized that a stationary armature winding would be an ideal one in some respects, but it was thought that any rotating field construction was bound to be a difficult and expensive one. The inductor type construction was supposed by some engineers to overcome the objections to the rotating field, but many others considered that this type was not a final one, as it did not use the magnetic material in the machine to the best advantage. In the earlier alternators, with insufficient ventilation through the armature core, relatively low magnetic densities were necessary to avoid excessive iron heating, and the inductor alternator, with its non-reversal of armature flux, was worked at almost double the induction of the rotating armature type of machine, and thus the disadvantages of the non-reversal of flux of the inductor type were masked. In other words, the inductor alternator was worked well up toward saturation, while the other types were worked at only about half saturation. However, with improvements in ventilation due to radial ventilating ducts, improvements in iron by better annealing and painting of the laminations, etc., the flux densities in the rotating armature machines were gradually increased until high densities, approaching saturation, were reached. A corresponding increase in flux densities

in the inductor type was not possible, on account of saturation. Therefore the rotating armature type of machine, in the later designs, was much more economical than the inductor type, although the latter had a very considerable advantage, especially at high voltages, in its stationary armature construction. Due to the merits of the stationary armature construction, the present rotating field type of machine was gradually evolved, which possesses the advantages of the stationary armature of the inductor type machine and the reversing flux of the rotating armature alternator. It was the development of this type of machine which sounded the death-knell of the inductor type. However, the Westinghouse Company, about 1897, decided to bring out a line of inductor type alternators to meet market conditions, although such decision was contrary to the recommendations of the designing engineers of the company, whose recommendation in particular was in favor of the rotating field construction as a more permanent type. However, as the rotating field type was not yet established, except in a very minor way, and as the inductor type had been on the market for years, it was decided to build the inductor type, although the design adopted was somewhat different from the Stanley type. Three sizes of these machines were built, two belted and one engine type, but the inductor type, as a commercial proposition, soon died out.

One of the interesting peculiarities of the inductor type alternator, as usually built, was in the enormous stray field appearing in the shaft, bearings, bedplate, and sometimes in the engine-governing mechanism in engine type units, necessitating in at least one case, the use of brass governor balls. In the usual construction of inductor alternator, there was but one exciting winding. The magnetic circuit and the field winding were arranged as in Fig. 8, which shows both the Stanley and the Westinghouse constructions. The normal or useful path of the magnetic flux is indicated by the dotted lines *a*, *a*. Obviously, the field coil which set up flux through these paths could also send magnetic fluxes through the shaft, bearings and bedplate along the dotted lines *b*, *b*. Moreover, if the two bearings were not connected by a magnetic bedplate, as might be the case in engine type machines, then, in two-crank engines the engine cylinders and other parts became opposite poles of a very powerful electro-magnet, when the field coil was excited. The stray magnetic field set up in engine type units was sometimes so strong as to interfere with the

governing mechanism. Also, with a strong unidirectional flux between the bearings and shaft, each bearing became part of a small unipolar generator, of which the bearing surfaces formed the brushes. In some machines, quite heavy currents were generated in the bearings, sufficient to "eat away" the bearing surfaces or to pit them so that bad bearing operation resulted. As this was primarily a magnetic trouble, insulating the bearings from their pedestals would not stop the action. To overcome this trouble,

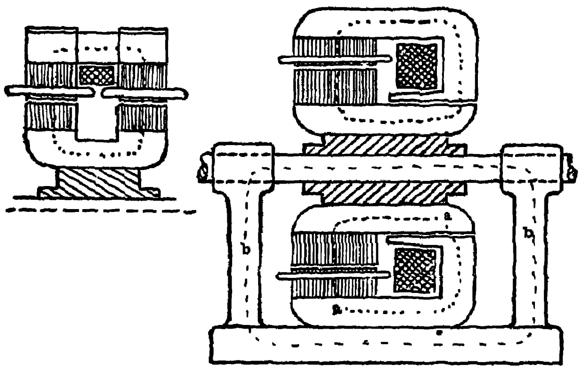


FIG. 8—SKETCH OF MAGNETIC CIRCUIT OF AN INDUCTOR ALTERNATOR

the Stanley Company added a "bucking " coil placed around the shaft at one side of the generator, this coil being in series with the main field winding and magnetizing in the opposite direction. The ampere-turns of this bucking coil being made equal to those of the field coil, the resultant ampere-turns between the two bearings would be zero. Obviously, in an alternator with a bedplate and two bearings in which the armature frame rested directly on the bedplate, a single bucking coil at one side of the machine would not neutralize the stray field through both bearings.

Rotating Field Generators

Considering next the rotating field type of machines, possibly the earliest example was the Niagara type, mentioned before. This had an internal stationary armature, with windings on its outer periphery like the ordinary rotating armature. Outside this was the rotating field, consisting of a heavy forged steel ring with inwardly projecting poles. However, this type of construction was relatively expensive, and was never adopted generally. The more modern

rotating field type of alternator, with external stationary armature, was a rather gradual development and, during this period, there was much heated discussion as to the relative advantages of the rotating field and rotating armature types. The rotating field gradually superseded the rotating armature construction for a number of reasons, the principal one having to do with the armature windings and voltages. In the rotating armature, the end windings were more difficult to support than in the stationary armature. Also, with the gradual advent of higher voltages, the stationary winding proved to be far superior. However, as a goodly proportion of the alternators built during this transition period were of the engine type and for low voltage, in which heavy bar windings could be used, (such being conditions under which the rotating armature made its best showing,) this type persisted for several years after the rotating field type became commercial. Gradually increasing voltages, however, necessitated the use of stationary armature machines, for at least part of the business. The manufacture of two types of apparatus for the same general purpose could not persist, and eventually that type was adopted exclusively, which allowed both high and low voltages. By 1900, the rotating field alternator had come into very general use, and the rotating armature type was disappearing. This rotating field type has persisted until the present time, although many minor modifications have been brought out from time to time, due largely to change in speed conditions, etc.

In the rotating field development, the tendency for a number of years was strongly toward the engine type construction and relatively low speeds in many cases. The construction was carried to the extreme, in some cases, where the usual flywheel capacity required for the slow speed engines was incorporated in the field structure of the alternator itself. In some cases, this meant enormously large machines for the output. A prominent example of this is found in the seventeen 6 000 kilowatt engine-type machines designed in 1899 and 1901 respectively, and installed in the Fifty-ninth and Seventy-fourth Street power stations of the Interboro Rapid Transit Company of New York City. As an indication of the changes taking place in the electrical field, it may be stated here that arrangements have been made recently to take out a number of these machines and install in their place 30 000 kw turbo-generator units. The existing engine type machines are probably in as good condition now as when first installed, and are

being replaced simply because they occupy too much space in proportion to their output.

The rotating field alternator of the early days was not radically different from the rotating field alternator of today, the principal

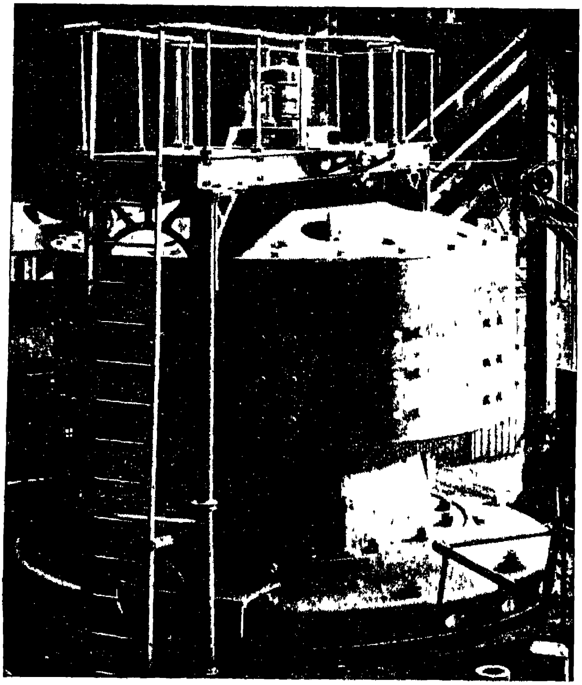


FIG 9—SHOP VIEW OF 5 000 HORSE-POWER TWO-PHASE NIAGARA ALTERNATOR

differences being in the type of armature windings, methods of ventilation, etc.

Field Construction

In the types of field windings there has been but little change. In many of the old stationary field machines of large capacity, the field windings consisted of strap wound on edge, one layer deep. For smaller machines, either square or round wire was commonly used. In the latter rotating field machines, similar constructions are used. In the construction of the field itself, there have been some variations and modifications. In many of the older machines the poles were laminated as at present. The method of

attaching the poles varied in different constructions. In many of the earlier Westinghouse rotating fields the laminations were punched with two or more poles in one piece, the poles having no overhanging tips, and the field coils being held in place by metal wedges between pole tips, fitted into notches or grooves at the pole tips, each pole being attached to the field ring or yoke by means of bolts or dove-tails. This latter construction possesses numerous advantages, in that cheap dies can be used, and the same pole punchings can be used for a number of different designs, in which either the diameter or the number of poles is varied.

Water Wheel Type Generators

With the advent of the turbo-generator on a large scale, the engine type rotating field alternator almost disappeared from the manufacturing field, except in the smaller size units. However, during this period there has been a gradual development in the use

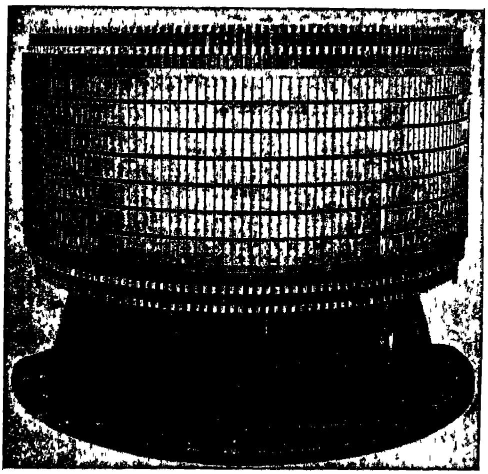


FIG. 10—STATOR OR ARMATURE OF NIAGARA ALTERNATOR

of water powers, and water-wheel driven generators have come into much greater prominence in the past few years. In this line of development, speeds and capacities, unheard of in the earlier days, have become accepted practice with the development of both high-head and low-head water powers. In the former the tendency has been toward very high speeds for a given capacity such

as the 17 000 k v.a., 375 r.p.m., Westinghouse machines, built for the Pacific Light & Power Company, and the 10 000 k.v.a , 600 r.p.m., Westinghouse generators, built for the Sao Paulo plant in Brazil. Typical examples of low-head, slow-speed practice are found in the 60 cycle, 75 r.p.m., 96 pole, 2 700 k.v a. Westinghouse generators for the Stevens Creek development, and the 25 cycle, 58 r.p.m , 52 pole, 9 000 k v a. General Electric generators for the Keokuk plant. The former are abnormal in the very large number of poles required for moderate output, while the latter are abnormal in the very low speed. Both of the above machines are of the vertical type, and are examples of a very pronounced tendency toward vertical machines, which has been apparent in the later water wheel practice.

On account of the high speeds of some of the modern rotating field alternators, mechanically stronger spiders have come into general use. Even in moderate speed units the usual high runaway over-speed of 100 percent has necessitated the use of very substantial spiders.

During the past few years, some very interesting spider constructions for the rotating fields of large high speed alternators have been built to meet the severe speed requirements. Some of these have been made up of cast steel centers or spiders with cylindrical rims built up of overlapping laminated punchings, thoroughly bolted together and attached to the spider by dove-tails. The outer periphery of the laminated ring carries dove-tail grooves for poles. In another construction, the entire spider consists of thick rolled iron plates, bolted together, and with dove-tail grooves on the outside for the poles. In still other constructions, the rim of the spider consists of a heavy steel ring in one or more sections to which the cast spider is bolted. Usually with this cast rim the poles are bolted to the spider. In some cases the rim forms an integral part of the spider itself, being cast with the spokes and hub. The type of construction adopted in each case is, to a large extent, dependent upon the stresses to be taken care of, so that no one type seems to fit all cases to best advantage

The Problem of Ventilation

In the later rotating field alternators the problem of ventilation has received much consideration, especially in the case of machines operating at abnormal speeds: In very high speed machines of very large output the armature and field cores have

a ratio of width to diameter which is relatively much greater than in ordinary machines, and this has necessitated abnormal conditions of ventilation. Something may be said here regarding the general problem of ventilation of alternators and its influence on the evolution. Back in 1891 or 1892, radial ventilating ducts or passages came into use commercially on certain direct-current machines. The results being quite satisfactory, it was natural that alternators should have the same method of ventilation. The use of such ducts was in reality one of the great steps forward in the evolution of dynamo-electric machinery, although but little recognition has been given to this fact in electrical literature. The use of radial ventilating ducts has continued to the present time with little change except in the construction of the spacers themselves, which have been many and varied in design and materials. With the change from the rotating armature to the rotating field construction of alternators this feature was retained in full. In some of the earlier Westinghouse rotating field machines the field structure also had numerous ventilating ducts, principally for the purpose of supplying ample air to the armature ducts. Also, about ten years ago, special ventilating end bells and vanes began to be used on rotating fields, in order to set up an extra air circulation through the armature end windings, etc., due largely to the fact that the slow-speed engine-type machines of that period did not have much natural blowing action. Following this, and partly as an outgrowth of turbo-generator enclosing, came the semi-enclosed alternators, mostly for high-speed water-wheel driven units, and this practice is not uncommon at present.

The proper ventilation of an alternator or, for that matter, of any dynamo-electric machine, is very much of a problem, for no two cases, in different sizes or types of machines, are quite alike. The problem lies first, in furnishing the proper quantity of air to carry away the heat developed, and in then distributing such air in proper proportion through the complex multiple paths in the machine. The proper distribution of the ventilating air is usually the most serious part of the problem. The present solutions of the problem are based largely upon past experience, and no really workable rules have yet been developed. In arriving at the present practice many disheartening experiences have been undergone by all designing engineers. The writer has known many cases where totally unexpected results, both good and bad, have been developed and, in some of these cases, no logical explanation was forth-

coming, so that the results could not be taken advantage of, with any assurance, in future work. This has been one of the most discouraging features in the general problem of ventilation.

Armature Windings

Something might be added here on the subject of armature windings. There have been probably as many types of armature windings developed as there have been types of alternators. The windings for the earliest smooth body and the toothed armature constructions have already been described. In the early Westinghouse polyphase alternators, two-phase was used mostly, due principally to the fact that single-phase lighting circuits formed the principal load, and, with two-phase machines, there were only two circuits from a machine instead of three circuits with the three-phase winding. Moreover, many of these very early polyphase

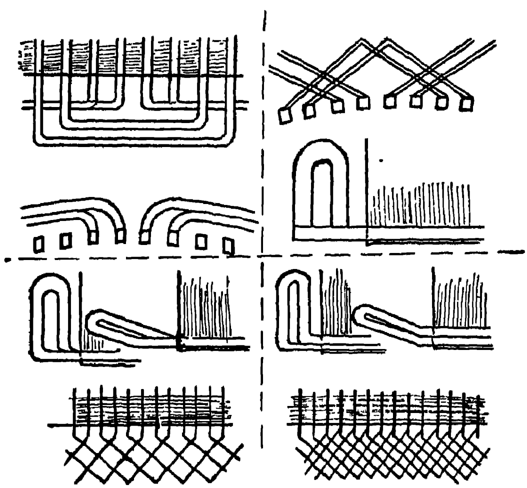


FIG. 11—VARIOUS TYPES OF EARLY STATIONARY ARMATURE WINDINGS

alternators were used in reality as straight single-phase machines, taking current off one phase only. For this purpose a closed coil armature winding, like that of a direct-current generator or rotary converter, with four taps for taking off the two phases, gave about the most economical type of winding, as far as armature copper losses were concerned. When such an armature is used for single-phase it can deliver seven-tenths as much output

as a single-phase machine as it can give two-phase with the same total copper loss per coil. It was partly for this reason that many of the early Westinghouse polyphase machines had a single closed coil winding. Another reason for such winding was that there were no definite phase groups and no high potential between phases. Furthermore, the arrangement of the end windings was such that the coils tended to interlock and support each other, thus assisting in resisting centrifugal forces. This winding was used mostly for two-phase machines, but was also used to a considerable extent on three-phase armatures.

With the advent of the rotating field type of machine, this closed coil type of armature winding was not used to any great extent, open-coil two-phase and star-connected three-phase taking its place. Delta-connected three-phase was used in very rare cases, as there was danger of circulating current with such windings.

In the construction of armature windings possibly more radical changes have taken place than in the types of windings. Many of the larger low speed rotating armature alternators had bar windings with separate end connectors, soldered or bolted on. Many of the earlier stationary type armatures had either built-up bar or strap windings, or concentric type windings in which each phase winding was arranged in a concentric group, and the groups of the different phases overlapped each other. Some of these were made with partially closed slots and others with open slots. The built-up bar or strap windings were frequently of the partially closed slot type, while the concentric windings were more usually of the open slot type. Gradually, however, both these types of windings were superseded by the "duplicate coil" type of winding, similar in appearance to the usual direct-current armature and induction motor primary windings. This later type of alternator winding was arranged in two layers of coils at the ends, in either one or two layers in the slots. The two-layer, two-coil per slot arrangement is now practically the standard. These types are illustrated in Fig. 11.

In the rotating field machines, partially closed slot construction was carried to comparatively high voltages. For instance, the 6 000 kilowatt, 75 r.p.m., 11 000 volt, three-phase generators built for the Manhattan Elevated Railway in 1900 had three bars side by side, in each slot, with soldered-on end connectors.

As the partially closed slot and the open slot constructions are radically different from each other, something should be said regarding the reasons which prompted the use of either type. As already indicated, the partially closed slot type came in with the larger rotating-armature low-voltage alternators in which bar windings could be used This construction gave good mechan-

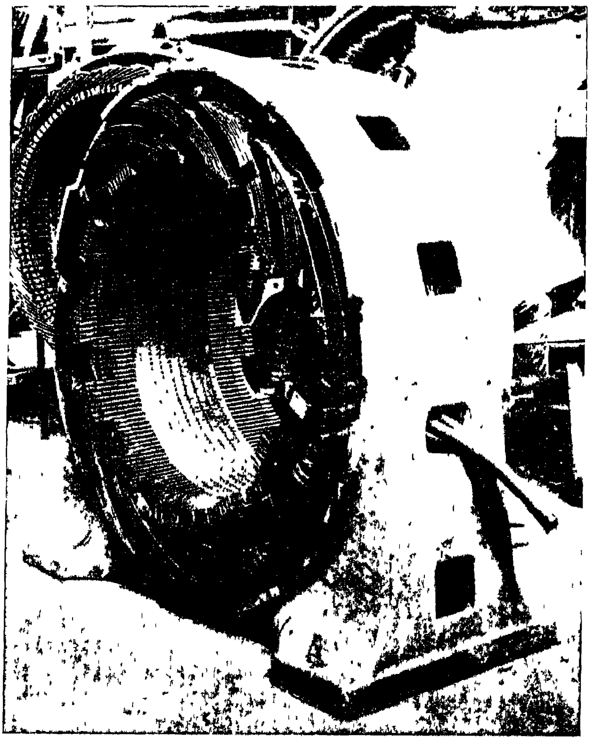


FIG. 12—BAR AND END CONNECTOR TYPE OF WINDING WITH PARTIALLY CLOSED SLOTS

ical support for the bars in the slots, thus avoiding the use of bands. Moreover, with the very narrow slot openings at the top of the slots, there was very little "bunching" of the magnetic flux at the armature tooth tips with the consequent low pole face losses, even with very small air-gaps, and high gap flux densities. The disadvantages of the partially closed slot is found largely in the type of windings required.

In these early machines, it was found practicable, in general, to use completely formed and insulated coils with such slots, and therefore, either hand windings or built-up types of windings were used. While these were possible and practicable in a manufacturing establishment, yet such types of windings are usually difficult to repair by the ordinary operator inexperienced in the refinements of armature winding. When it comes to repairs, the usual machine-wound coil, which is completely insulated before being placed on the armature core, is very superior but, in general, this type of winding requires an open slot construction. However, when

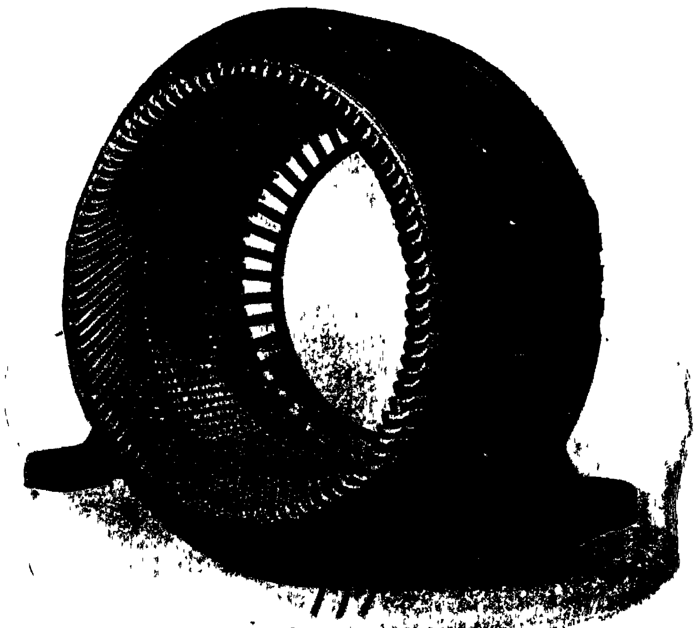


FIG. 13—DUPLICATE COIL TYPE OF WINDING, TWO COILS PER SLOT

the stationary armature construction came into general use, the advantages of the overhanging tooth tips in supporting the coils largely disappeared. There remained therefore the disadvantages of the flux bunching, against the advantage of coil construction, if open slots were used. However, the use of laminated poles, and the judicious proportioning of the air-gaps and flux densities, to a great extent eliminated the losses due to open slots. In conse-

quence, the open slot construction and the duplicate type of armature coil, have apparently come to stay, in this country.

Various attempts have been made to obtain the advantages of both the open and the partially closed slot arrangements. Probably all large manufacturers of alternators have tried some form of magnetic wedge, instead of the usual fibre or wood wedges which serve to retain the coils in the slots. Another arrangement is the equivalent of combining two or more open slots in one, with an over-hanging tooth tip, which covers the slot with the exception of the widths of one coil. Two or more completely insulated coils are fed successively into the slot opening and arranged side by side. This does not give any narrower slot opening than with the open slot construction, but the number of openings is reduced to one-half, or one-third. This construction is used rather extensively in the rotors of large induction motors, but apparently is but little used in generators.

Bracing of the end windings against short-circuit shocks has been a comparatively recent practice. The necessity for such bracing has been dependent to a considerable extent upon the output per pole, and the old time machine seldom had such a large output per pole that the short-circuit current-rushes were sufficient to cause dangerous distortions of the end windings. However, such bracing was used on the Niagara machines, previously described, and also on the Manhattan generators above referred to. These, however, were very rare instances. However, with the recent high-speed, high-output water-wheel generators, the outputs per pole have become such that some form of end bracing has become rather common.

Modern Westinghouse machines of this kind are braced to stand a dead short-circuit across the terminals without damage to the windings. Under this condition, these large machines may give a momentary current rush of from ten to twenty times the rated full-load current. However, the bracing required on the end windings of such machines is of relatively much less importance than on turbo-generators of corresponding capacity, due to the fact that, in the former class of machines, the end windings are relatively short compared with those of turbo-generators.

The above description brings us practically up to date, as far as the ordinary synchronous alternator is concerned. No description of the development of the turbo-generator has yet been given. This forms a rather distinct development which should

follow at this point presumably, but it is thought advisable to interpolate here some description of the problems of parallel operation, e. m. f. wave form, regulation, etc., which came into prominence and were practically taken care of previous to the advent of the turbo-generator on a large scale.

Parallel Operation of Alternators

One of the great problems which developed in the operation of alternators was that of the parallel running of two or more units. At one time this was a very serious question, but in recent years, it is very seldom heard of. Considering the almost universal

FIG. 14—DETAIL VIEW OF THREE-PHASE CONCENTRIC WINDING

practice of paralleling alternators, which holds at the present time, one might be led to wonder why there ever was any trouble. Far back, in the days of the high-frequency surface-wound alternators, paralleling was attempted in many cases and, not infrequently, with considerable success. However, a failure in an attempt to parallel, in those days, usually meant the destruction of the apparatus. Those old time surface-wound alternators usually had very low self-induction, so that, in case of sudden short-circuit, an enormous current could flow, sufficient usually to strip the arm-

ature winding from the core, by bursting the bands, or otherwise. A failure in an attempt to parallel two machines was practically equivalent to a short-circuit, and this usually meant destruction of the apparatus. However, if once paralleled successfully, the machines usually did not act badly. One favorable condition, not then appreciated, was that all these early machines were belt-

FIG. 15—75 K.V A., THREE-PHASE, 60 CYCLE, 2 300 VOLT, 150 R. P. M. ROTATING FIELD ENGINE TYPE ALTERNATOR

driven. It may be said, however, that in those days parallel operation, while considered possible, was also considered more or less risky. In the period immediately following the surface-wound alternator, parallel operation was very much the exception, rather than the rule and, when engine-type alternators came into use, paralleling was considered for several years as very questionable. At this time the situation was as follows:—Belted alternators could be paralleled in many cases. Direct-coupled alternators,

if flexibly driven, could be paralleled almost as well as belted machines, while direct-coupled or engine type generators, without flexible coupling or drive, could not be relied on to parallel without hunting. It thus became recognized that some flexibility between the generator and its prime mover was an important adjunct to parallel operation. This led to the consideration that the engine might be back of the difficulty in many instances, and it was then assumed that inequalities in the regular rotation resulting from insufficient flywheel or from hunting governors, tended to cause hunting in the generators. Investigation showed that such conditions did tend to produce hunting, but that the magnetic conditions in the machine itself would oftentimes maintain, or even accentuate, the hunting. Obviously, therefore, the trouble was both in the prime mover and in the generator. It was noted further that if the angular fluctuations in the driving power were relatively small, hunting usually would be very small, or would not be apparent at all. It was further recognized that, with belt or flexible drive, which tended to smooth out the speed fluctuations due to the prime mover, the hunting tendency tended to disappear. Attention was then turned toward improvement of the prime movers, especially in engine-type machines, in order to reduce fluctuations in angular velocity by means of heavy flywheels, and by means of dampers of some sort, such as dashpots, on the governing mechanism of the engine. Much improvement was accomplished in this way.

The Introduction of Dampers

During this period many attempts were made to lessen the tendency of the alternator to maintain hunting. Investigation showed that, during hunting, the magnetic flux in the field poles shifted back and forth across the pole faces in time with the hunting, while such action did not occur when there was no hunting. This at once led to the theory that a low resistance winding on the pole face, or imbedded in the poles, would prevent or oppose this flux shift, and thus assist in overcoming hunting. However, about this time, rotary converters were coming into use, and it was found that, in such machines, hunting was usually more severe than in alternators, so that, in this country, the first true application of damping windings or devices to stop hunting were applied on rotary converters. It was also noted at this time that solid pole generators and rotary converters did not hunt to the same extent as did laminated pole ma-

chines, and it was correctly assumed that the solid pole faces gave an effect similar to that of low resistance damping windings. However, as it was desirable to use laminated pole tips, copper dampers on the poles gradually came into use. Some of these early dampers were very crude in form and type compared with present construc-

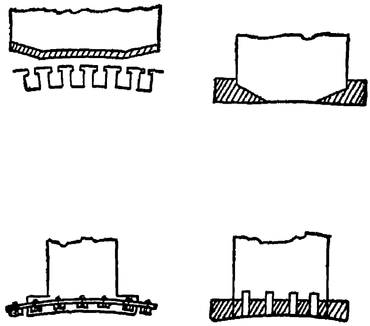


FIG. 16—VARIOUS FORMS OF DAMPERS

tions. However, imperfections in the construction of the dampers were balanced to some extent by the large section of copper used and consequent low resistance. The earliest form of damper used in this country consisted of copper rings surrounding the poles and

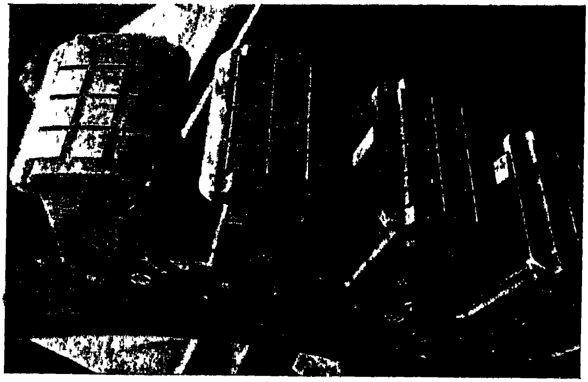


FIG. 17—GRID DAMPERS ON FIELD POLES

copper tips overhanging the beveled pole edges. This was the form most commonly used on converters. On alternators, in some cases the damper consisted simply of a low resistance ring around each pole. In still other cases the damper consisted of a heavy copper plate covering the pole face. This latter construction was only

possible in machines with large air-gaps and very narrow or partially closed armature slots. These crude forms of dampers were gradually superseded by the so-called "grid" damper which consisted of a copper grid surrounding the pole and with ribs which lay in slots in the pole face. These various types of dampers are shown in Fig 16. In very few cases were these old types of dampers so interconnected as to form a complete cage winding around the field.

Many tests were made at various times to determine the effect of interconnecting the grids on the different poles to form one complete cage. As a rule, there was no appreciable gain, and it was then assumed that such interconnection had no material advantages. However, it later developed that the reason why interconnection of the dampers did not improve the damping action very materially, was due largely to the very great amount of copper in those parts of the grid dampers lying between the poles. The grid damper was very effective, but was expensive in material, and was not easily applied on poles with overhanging

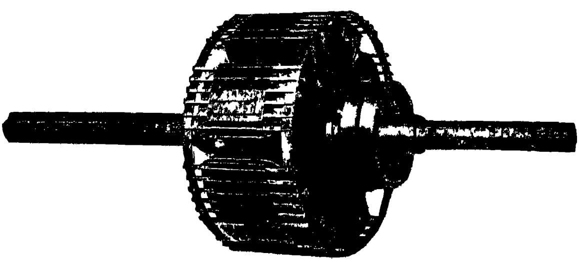


FIG. 18—CAGE WINDING TYPE OF DAMPERS

pole tips. This type of damper was gradually superseded by one similar to the usual cage winding on the secondaries of induction motors, and this is the type which is in most general use at the present time. This construction has practically the same effectiveness as the old grid type, but is much more economical in material and, being placed in partially closed slots, it does not as greatly affect the iron losses in the machine, as was liable to be the case with the open slots, generally used with the grid damper.

With the gradual introduction of dampers and improvements in angular rotation of the prime movers, hunting troubles in alternators practically disappeared, and parallel operation presented

no difficulties, except under very abnormal conditions. Apparently these dampers or "amortisseurs," as they are sometimes called, were first proposed by the French engineer, Maurice LeBlanc, about 1891. However, they were "rediscovered" in this country by engineers who were not familiar with the above engineer's work.

Voltage Wave Form

The e m. f. wave form of alternating-current generators has been a matter of much discussion since the early days of alternator design. The old surface-wound machines gave a very close approximation to a perfect sine shape, due to the arrangement of the winding and to the very large air-gap. The first toothed armatures, with their very small air-gaps, gave e. m. f. waves which

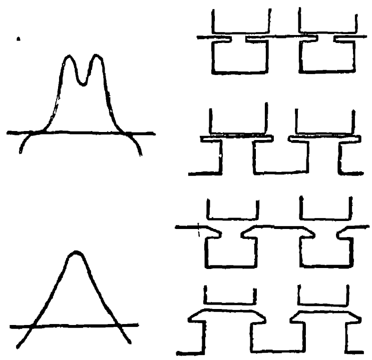


FIG 19—VOLTAGE WAVE FORMS

Of early toothed armature machines and of later toothed armatures with larger air gaps and beveled poles.

departed very widely from a true sine. In fact, this had about the worst wave form of any of the alternators which have been put out by the Westinghouse Company. Its shape was somewhat like that shown in Fig. 19, as would now be expected when the configuration of the armature tooth tips is taken into account. The later toothed armatures with large air-gaps and beveled tooth tips gave much better wave shapes.

With the advent of the true polyphase windings and the slotted armatures with several slots per phase per pole, fairly close approximation to sine shaped e. m. f. waves became common. In the first Niagara Falls 5 000 horse-power, two-phase alter-

nators, the voltage wave was slightly flattened on the top due to the fact that the pole face width was somewhat greater than the width of each phase group in the armature. When very high voltages came into general use, and especially in machines with small pole pitch, the number of armature slots per phase per pole was reduced to a minimum in order to lessen the total insulation space. In extreme cases, but one slot per phase was used, giving but two slots per pole for two-phase and three slots per pole for three-phase. Such windings required special shaping of the field pole tips in order to approximate even roughly a smooth wave form of the sine shape. Later practice, however, has tended toward the equivalent of at least two slots per phase per pole, in order to obtain better results. Sometimes the desired result is obtained by the use of one extra idle or "hunting" tooth per phase.

In the early days of parallel operation of engine type alternators which, as described before, represented the most difficult conditions, great stress was laid upon the question of wave form in some of the discussions of parallel operation, and particularly, in the operation of rotary converters without hunting. Gradually, however, this question disappeared and it became recognized that all the cases of hunting encountered could be explained in some other way than by the e. m. f. wave forms, and it is now generally accepted that about the only effect on parallel operation due to wave form lies in possible circulating currents of higher frequency than the fundamental.

At the present time, a very close approximation to the sine shaped wave is considered preferable for general purposes, especially in transformation and transmission work. There have been some instances of telephone disturbances due to wave form but, as a rule, some local peculiarities of the distribution circuits have been involved in this trouble, for, in other cases, similar or even worse shaped waves have given absolutely no telephone disturbances.

Regulation and Compounding

Something should be said on the subject of regulation of alternators, for this is a very important characteristic, and has had considerable influence on types and designs. The old surface-wound alternators had extremely good regulating characteristics due to their low armature self-induction and low armature reac-

tion consequent upon their large air-gaps. The writer does not know what value the current rose to, on steady short-circuit, compared with the normal rated current, but it was probably four or five times full load. The current rush on short-circuit was probably five times as great as the steady value. It is not to be wondered at that such armatures not infrequently wrecked themselves in case of a dead short-circuit. In the later toothed armature types, the armature self-induction and reaction on the field were very much larger, proportionately, than in the surface-wound machines. This, however, spoiled the regulation and some method of compounding was used, as already described. This compounding was common practice until larger capacity machines, especially the engine type, came into use. Even some of these latter were compounded by commutating the armature current (either directly or from a series transformer) and compounding the exciter field by means of the commutated current. A few of the smaller size alternators were both self-excited and compounded by commutating derived alternating-current circuits from the armature. This, however, was found to be very delicate, as the excitation and compounding were greatly affected by changes in the power-factor of the load, and by changes in speed.

One early attempt was made to compound single-phase alternators to correct for power-factor. In this case the commutated armature current was sent through the series or compound winding of the exciter. The brushes on the alternating-current commutator were so set that at 100 percent power-factor they were commutating about the middle of each voltage wave. In consequence, the current delivered to the brushes was not a true direct current but consisted of a double number of half waves, half of which were inverted, and the direct-current component of this commutated current was small and had but little compounding effect. However, with change in power-factor of the load, the phase of the current shifted, so that at some reduced power-factor, commutation occurred at the zero point of the current waves and the resultant current was all effective for magnetizing the exciter field. The total commutated voltage was very low and the commutator bars were shunted by a resistance so that there was no bad sparking, even when commutating at the middle of the current wave. This method did actually compound fairly well for change in power-factor, but the field for such method proved to be very limited, for compounding of alternators fell into disuse shortly after this.

The usual method of compounding on the early alternators was simple series-current compounding, just as in direct-current apparatus. Where the commutated current was supplied directly to the field compound winding, voltages of about 30 to 60 volts were most common at rated full load. With much higher than 60 volts, there was a liability of short-circuiting the compounding by arcing between bars on the commutator There was also a liability of arcing or flashing when the phase of the current shifted due to change in power-factor.

When polyphase rotating armatures came into use, similar methods of compounding were resorted to. However, the secondary current was a resultant of the two, or three primary currents, for each of the primary phases was carried around the compensating transformer (or spokes of the armature) and the secondary winding carried a current in phase with the resultant of the primary ampere-turns. In the case of three-phase windings, the direction of one lead was reversed around the compensating transformer. Some curious conditions arose from the phase relations of the secondary current when parallel operation was practiced. It was necessary, when paralleling the main winding, to parallel also the compound winding. As the compounding current from each machine pulsated from zero to maximum value in each alternation, it was necessary to so parallel the terminals that all the commutated currents had zero value at the same instant, otherwise, the brushes on one commutator would, at times, short-circuit the current from the other commutator.

With the advent of larger belted machines, and of engine-type machines in particular, the compounding of polyphase machines was more or less unsatisfactory and was practically abandoned. To compensate for the lack of compounding, better inherent regulations were aimed at in the designs. This meant, primarily, machines which would give comparatively large currents on steady short-circuit, three to four times full load being rather common, and even six times full load being attained in some machines. The momentary current rush at the instant of short-circuit must have been excessive on some of these machines, due to their very low armature self-induction. However, due to the relatively small ampere-turns per pole, no very destructive distortions were found in practice. This characteristic of the short-circuit currents was carried into the rotating field construction, and even into the early turbo-generator work.

This practice of giving the alternators good inherent regulation was expensive in a number of ways, as it usually meant higher iron losses and less output than was possible otherwise, with a given size machine, or a given amount of material. Even at this early date, it was recognized that some form of automatic field current regulator which would maintain the terminal voltage constant, regardless of the inherent regulation would be a very useful piece of apparatus. Some form of regulation which would take care of change in power-factor, as well as load, was the aim of many designers. Among the different schemes brought out, the Rice method of compounding, brought out by the General Electric Company, is of interest. This was used principally with rotating field alternators. In this scheme, the exciter was usually placed on the same shaft as the alternator field, and, in such case, had the same number of poles as the alternator. The leads from the alternator armature were carried through the exciter winding in such a way that a lagging current, carried by the alternator, tended to strengthen the field of the exciter by shifting the armature reaction with respect to the exciter field poles. In this way a compounding action on the exciter was obtained which was practically in proportion to the demands of the alternator field with varying power-factor. In the case of engine-type machines of comparatively low speed, the exciter was geared to the alternator shaft, so that it ran at a considerably higher speed and the number of poles in the exciter was correspondingly reduced

This method of compounding was effective, but the whole combination was apparently unduly complicated and expensive. Furthermore, it did not give the desired compensation under all conditions of operation, as it would not correct for changes in speed.

A later method of compensation for power-factor was devised by Alexanderson, and was used on a limited number of General Electric machines. In this scheme a derived current from the alternator itself was commutated in such a manner that compensation, proportional to the power-factor, was obtained. This was a purely self-excited alternator scheme and, like all self-exciting schemes in such apparatus, it was sensitive to speed changes, probably to a much greater extent than the Rice arrangement above described. A fundamental defect in all self-exciting compensated alternator schemes lies in the fact that stability of excitation is dependent upon having considerable saturation in the

alternator magnetic current and, coincidently, if there is such saturation, the compound current has no direct relation to the load or power-factor. Thus such machines are either sensitive to speed changes, or their compounding is only approximate.

Following these schemes came the use of automatic regulators of which the Tirrill is best known. This regulator acts directly on the exciter field by short-circuiting a resistance in series with the field winding, the range of exciter voltage being controlled by the length of time the rheostat is short-circuited. Instead of cutting the resistance out in steps, which tends to give sluggish action in the fields, the Tirrill regulator cuts the whole resistance out each time, and the length of time is varied. This results in quick action. As the regulator tends to hold constant voltage at the alternator terminals, or on the line, change in power-factor or in speed does not modify the action. This type of regulator has proven very effective, especially in the case of alternators subjected to sudden and violent changes in load, power-factor and speed.

With the advent of larger alternator units, in proportion to the changes in load, the inherent regulation has been made relattively poorer, primarily because better machines otherwise are thus obtained. The short-circuit currents are reduced, and relatively lower iron losses, and lower temperatures or, higher outputs with a given temperature, are obtained. This has been carried further in turbo-generator design than in any other class of alternators, due partly to fundamental limitations in design. However, this poorer inherent regulation has proven to be of no practical importance, where suitable automatic regulators have been used with the machines.

One fallacy which was frequently found in the past, and which still persists to some extent, is that alternators should have equal inherent regulation to parallel properly. This is based partly on the feeling that the field currents of the alternators should vary over equal range when carrying their proper proportion of load, together with the knowledge that the variations in field current are dependent, to some extent, upon the inherent regulation. However, the fact that the shape of the saturation curve, in a given alternator, may have much more influence on the excitation, especially at high saturations, is usually overlooked.

Turbo-Generators

The advent of the turbo-generator has had a predominant influence on alternator design. After the turbo-alternator once became established commercially in this country, it quickly revolutionized conditions by driving the large engine-type alternators out of the field. The evolution of all electrical apparatus has been comparatively rapid, but that of the turbo-alternator has possibly exceeded anything else in the electrical field. This evolution therefore merits a fairly complete description.

The first turbo-alternators built by the Westinghouse Company, were installed in the power plant of the Westinghouse Air Brake Company about 1898. These were three rotating armature machines of 300 kilowatts capacity, which ran at a speed of 3 600 r. p m , giving 7 200 alternations per minute, or 60 cycles per

FIG. 20—FIELD OF EARLY ROTATING ARMATURE TURBO-GENERATOR

second. They were coupled to Parsons turbines, built by The Westinghouse Machine Company. The Parsons Company in England had been building rotating armature alternators for a number of years, and the Westinghouse Company simply followed the Parsons' precedent. These first machines were operated for several years, but it was obvious, soon after their installation, that the rotating armature type of machine would not serve for

general turbo-alternator purposes. It was evident that, for voltages even no higher than 2 200, the rotating armature construction, at the necessary turbo-generator peripheral speeds, would become almost impracticable. Attention therefore was soon turned toward a 3 600 revolution,two-pole, rotating field type,

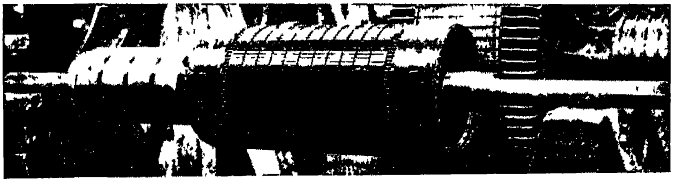


FIG. 21.—ARMATURE FOR TURBO-GENERATOR OF THE TYPE SHOWN IN FIG. 20

and a very large number of possible constructions were considered. Finally one like that shown in Fig. 23 was worked out and built in 1899. This had the field windings completely embedded in a number of parallel slots, with supporting metal wedges

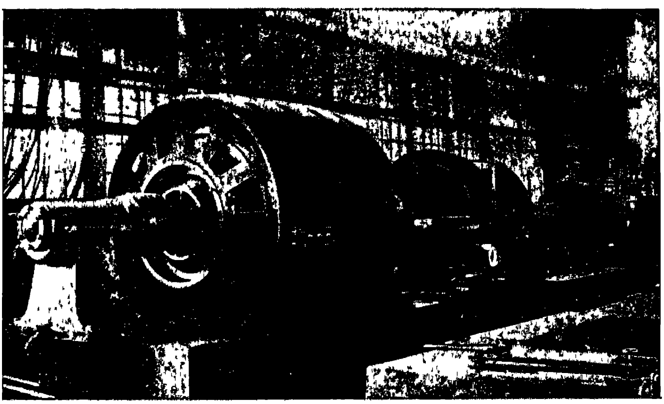


FIG. 22—1 000 KW OPEN TYPE TURBO-GENERATOR

at the tops of the grooves or slots. One machine of this type was built and tested. It operated in a satisfactory manner, except as regards windage and noise. The machine was not closed at the ends, like modern turbo-alternators, and thus any noise generated in the machine could be readily transmitted to the outside. The noise was caused largely by the two flat sides of the rotor. It was

so shrill and penetrating that it was very disagreeable to be around the machine, and was even painful to the ears after a short time. This construction was therefore abandoned temporarily, but after a few months it was taken up again and a new rotor was built which was entirely round, as shown in Fig. 24, but was otherwise very similar to that shown in Fig. 23. This new rotor, although noisy compared with modern machines, was so quiet, compared with the first construction, that it was immediately adopted as a standard construction. This is the now well-known parallel slot construction which has been used very extensively by the Westinghouse Company, although many very radical changes have been made in the constructive features of the rotor itself. This type of rotor was used originally only for the 400 kilowatt size at 60 cycles.

In the earlier machines of this type a number of very curious conditions developed. In the first machines the rotors were built of a number of thick discs or "cheeses" side by side, which were put on the shaft at high pressure. The two end discs were thicker than the others in order to accommodate the grooves in which the rotor end windings lay. The discs were made of high grade forg-

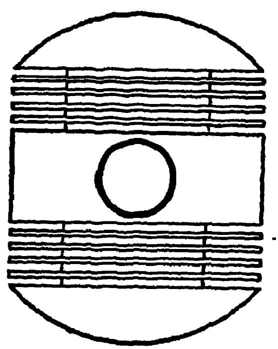


FIG. 23—EARLY TWO-POLE ROTATING FIELD

ings. After some of these machines had been in operation for a considerable period it was found that some of the discs in the field core were traveling axially, i.e., quite appreciable gaps or spaces were showing between adjacent discs. In one instance they traveled to such an extent that the field windings were stretched longitudinally at the openings between the discs, until the conductors were actually attenuated to an extent visible to the eye. Obviously, the stretching force must have been enormous.

Eventually, the construction was changed on these two-pole rotors to a single disc of forged steel. Still later, steel castings were used quite extensively instead of forgings although, later still, the castings were abandoned in favor of forgings. There was much adverse opinion regarding the advisability of using castings for the 3 600 revolution machines, as some engineers held that they were more liable to contain flaws than would be the case with forgings. An interesting fact in connection with this is that, while a number of these early high speed machines "exploded," generally during runaways, yet in no instance was a cast steel field wrecked from this cause. This, however, does not constitute a proof of the superiority of cast steel, for it so happened that all the serious runaways were on machines with forged rotors. However,

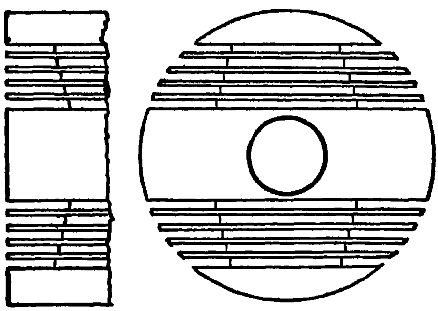


FIG. 24—ROUND TYPE TWO-POLE ROTOR

the record is a clear one as far as cast steel fields are concerned, for, of all the sizes and speeds of steel rotors which the Westinghouse Company has put out, not a single cast steel disc has burst. Present speed and output requirements have now carried the construction up to a point where special forged materials are the accepted practice.

Soon after the two-pole, 400 kilowatt rotating field machine was put on the market, a four-pole, 750 kilowatt, 1 800 revolution machine was built. The rotor of this machine had four salient poles bolted on. These poles were provided with overhanging pole tips, and the field winding consisted of four coils wound with strap-on-edge. In fact, this first construction was very similar to the present type of rotor fields now used for other than turbo work. This construction proved difficult and expensive, but was applied to a number of six-pole, 1 200 revolution machines. However,

the parallel slot construction used in the two-pole machines was so satisfactory that it was soon adopted for the four and six-pole machines, as shown in Fig. 25. In the six-pole machine it was not possible to make the poles integral with the central core, on account of the inability to machine the parallel slots in the sides of

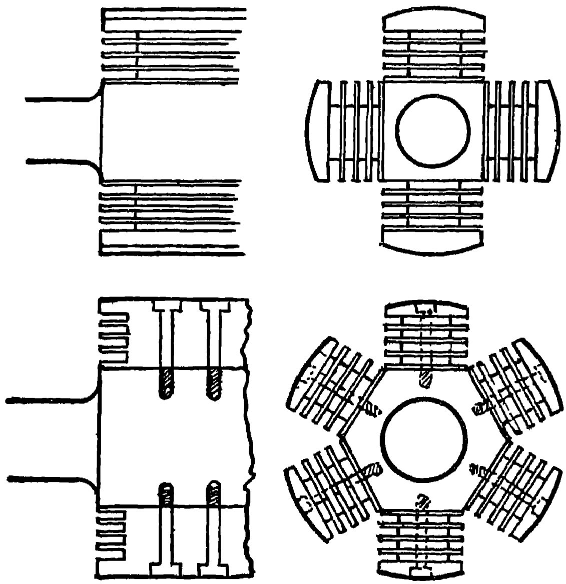


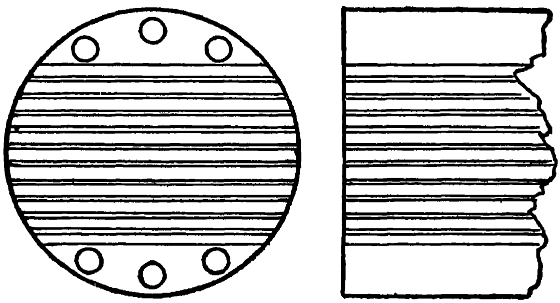
FIG. 25—PARALLEL-SLOT FOUR-POLE AND SIX-POLE FIELD CONSTRUCTION

the poles, or to put in the windings. Therefore, separate poles were constructed, with parallel slots, and these were first wound and then bolted into place on the central core which, in this case, was made integral with the shaft. The four-pole machine was constructed for 750 and 1 000 kilowatts capacity, and the six-pole construction was made for 1 500 to 3 000 kilowatts.

Meanwhile, there had grown up some demand for moderate capacity 25-cycle machines at 1 500 revolutions. These were constructed along exactly the same lines as the two-pole, 3 600 revolution machines above described.

In this early work one order for four 5 500 kw, four-pole, 1 000 revolution machines was taken. This was entirely beyond the constructions undertaken before by the Westinghouse Company. The parallel slot type of rotor was adopted. An attempt was made

to get forgings in a single piece large enough for these rotors, but they were found to be glass hard and brittle, except at the outer surface. As very large steel castings were frowned upon, it was decided to make these rotors of discs turned out of very thick steel plates, somewhat like the early 400 kw machines already described. Parallel slots were used as in the smaller four-pole machines. This construction proved to be feasible but was very expensive, and shortly after this, large cast steel discs were used, two discs side by side being used to form one rotor. This construction was satisfactory, and was used for many years



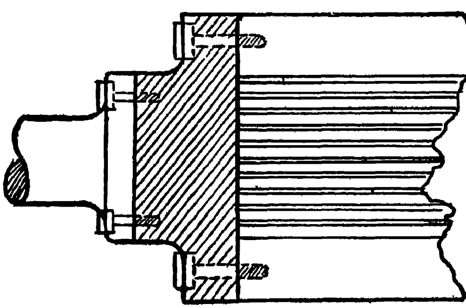


FIG. 26—TWO-POLE FIELD OF THE BOLTED ON CONSTRUCTION

Shortly after turbo-generators came into general use, there was considerable complaint regarding the noise due to windage. All these machines were equipped with some form of ventilating device, which either formed part of the normal construction of the rotor or consisted of some special blowing device at the ends of the rotor. Both the high speed and the large quantity of cooling air

required, tended to make a noise which was very objectionable. A series of experiments with covers over various parts of the machines, showed that, by completely enclosing the two ends of the machine and by enclosing the field frame except at the top and bottom, (in a horizontal machine) the windage noise could be so deadened as to be practically unobjectionable. However, the tests also showed that artificial ventilation was necessary under this condition. This very quickly led to the practice of enclosing and artificially cooling turbo-generators, which practice has been maintained to this day. The first Westinghouse enclosed machines were built about 1903.

The use of artificial cooling marked a great step in advance in turbo-generator work, for the results indicated that, by supplying a sufficient quantity of air and properly distributing it through the machine, very marked increase in capacity was possible, and a point was soon reached where the possible capacities were beyond the mechanical limitations of the construction. This led to radical modifications in the type of rotor, with a view to taking advantage of the increased capacity. Apparently all manufacturers did more or less development work along such lines. In the Westinghouse constructions, the use of a through shaft was found to be one of the serious limitations, and this led to types of rotors without any through shaft. In the two-pole machines, this was particularly important, and the problem was especially difficult with the parallel-slot construction, provided ample space was allowed for the field winding. The old through-shaft two-pole construction lost considerable winding space, due to the shaft space, as shown before in Fig. 24. Attempts to construct such a machine with the shaft forming part of the core, resulted in still less efficient use of the possible winding space. It was obvious that if the whole possible winding space were taken up with slots, then the capacity of the field winding would be greatly increased. In consequence, a rotor construction, such as shown in Fig. 26, was designed and constructed. In this, bronze end supports or "heads" were bolted to each end of the field core, and the shaft proper was attached to these bronze heads. Bronze, or a similar non-magnetic material, was necessary to prevent magnetic short-circuiting of the field flux. This design was constructed and tested on a 1 000 k.v.a., 3 600 revolution machine, and then was built successively for 1 500, 2 000, 3 000, 4 000 and 5 000 k.v.a. machines, all at 3600 r. p. m. The same construction was also applied to

two-pole machines of 25 cycles, up to 12 000 k.v.a. capacities. This construction of rotor has given an extremely good account of itself. However, it proved to be expensive on small capacity machines, as the bronze heads formed an undue proportion of the cost of material. For higher capacities of 3 600 r. p. m. machines, increase in capacity is obtained largely by increasing the length of the rotor core, and thus the bronze heads form a relatively lower percentage, and the construction becomes more reasonable in cost.

From the preceding, it may be seen that only two types of turbo-generators have been used very extensively, namely, the parallel-slot type and the radial-slot type. Each of these types has some very pronounced advantages. The principal advantage of the parallel-slot type is in the arrangement and support of the field coils. Each coil can be wound directly in place, with the conductor under tension, and the finished winding is completely encased, and is thoroughly protected against dirt, movement of the conductors, etc. Against this, the radial-slot machine allows more room for copper, and is magnetically more economical in material. However, the field windings are more difficult to apply and must be supported at the ends by auxiliary means, such as separate external steel rings.

The enormous increase in output of turbo-generators, within very recent years, has made the electric and magnetic proportions of the rotors a feature of first importance in the design, so that the radial-slot type for two-pole machines has become the standard construction, almost universally. This will be referred to again under the four-pole construction.

While the two-pole parallel slot construction was being developed for larger capacities, the four-pole construction for 60 cycle machines has been pushed up to capacities of about 12 000 k.v.a. with the parallel slot, cast steel rotors. In order to do away with the through-shaft construction, the rotor was made of two castings or discs, each of which was cast solid with the shaft, as shown in Fig. 27. The two discs, after machining, were bolted together by a number of very heavy bolts located near the pole tips and, in some cases, shrink links were placed in the pole face, connecting the two halves together. The parallel grooves were then machined in the steel core, just as in the through-shaft type. In this four-pole construction, the problem of armature ventilation was comparatively simple. Air-gap ventilation (that is, all air through the armature core supplied from air-gap) was easily

accomplished, due to the open spaces between the poles, which could admit an ample air supply. However, the same construction tended toward high windage losses due to air "churning."

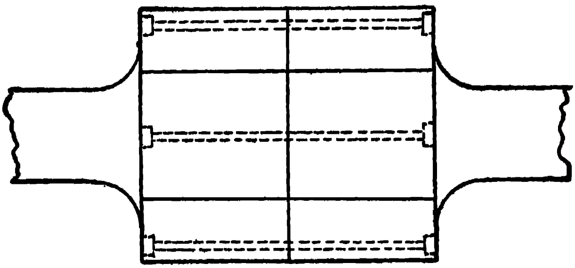


FIG. 27—FIELD CONSTRUCTION WITH TWO HALVES HELD TOGETHER BY HEAVY BOLTS

This problem of ventilation has had much to do with the evolution of turbo-generator design.* In the two-pole, parallel slot machine for 3 600 r. p. m., in which the diameter of the rotor is relatively small, the amount of air which can be forced into the air-gap from each end is rather limited. Assuming, for example, a rotor diameter of 24 inches, which is almost as large as we can go for a 3 600 r. p. m. machine, then, with an air-gap (iron to iron) of ¾-inch, which is also a fairly large gap, the total cross-section of the air inlet at the air-gap at both ends of the rotor will be 112 sq. in. With the very high air velocity of 10 000 ft. per minute, this means a total air supply of less than 8 000 cu. ft. per minute. This may be sufficient for a moderate capacity turbo-generator, but for machines of high capacities, such as 3 000 to 5000 k.v.a., this is not nearly enough cooling air. Obviously, either much larger inlets through the air-gap are required, or some additional method of cooling is necessary. Larger air-gaps usually mean either more expensive machines, or reduced output with a given machine, due to lower flux densities. Therefore, the tendency, in machines of the very high capacities, and very high speeds, has been toward a combination of air-gap with other methods of ventilation. In the 25 cycle, two-pole machine with a maximum speed of 1 500 r.p.m., rotors of larger diameter are possible and, as a rule, much larger air-gaps are practicable than in 60 cycle machines. In consequence, air-gap ventilation comes nearer being practicable but in

*A more complete exposition of the subject of "Turbo-Alternator Ventilation," etc., is contained in the paper on page 313.

the larger capacities, even this is insufficient and auxiliary methods have been necessary in some cases.

This need for auxiliary methods of ventilation led to the axial method of ventilating armature cores in distinction from the radial method, in which the air was carried out through numerous radial air ducts or passages. In the axial method, a large number of ventilating holes are arranged in the armature core parallel to the axis of the machine. These form ventilating paths in parallel with the air-gap path. With the small diameter long cores necessary for 3 600 r. p. m., high capacity machines, the development of this method of ventilation was contemporaneous with the development of the higher capacities. The same has proved to be the case for the later types of Westinghouse four-pole, 60 cycle, 1 800 r. p. m. machines, which departed very considerably in rotor construction from the four-pole cast steel type already described.

As the capacities of the 3 600 r. p. m , 60 cycle machines were gradually pushed up, a corresponding development occurred in the 1800 r. p. m. machines. At 10 000 to 12 000 k.v.a., the four-pole cast steel construction was apparently approaching its limits.

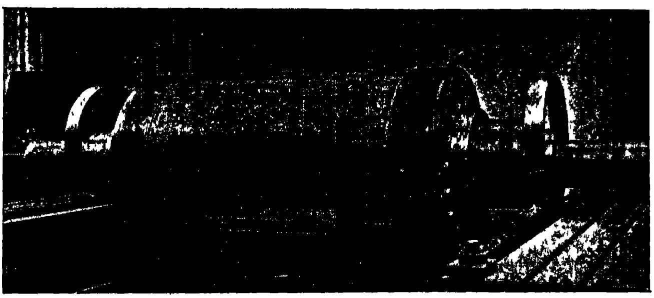


FIG. 28—MODERN ROTATING FIELD ON BALANCING WAYS

For larger sizes, therefore, a different construction was adopted which allowed more suitable material to be obtained. For the largest diameters and highest speeds, a plate construction was adopted by the Westinghouse Company, in which the end discs and the shaft ends were forged as units, and the intermediate discs were made of rolled plate material, the whole construction being bolted together permanently to form a solid core. This core was then slotted with radial slots, and the usual radial slot type of field winding is used. A similar construction was adopted on the larger 25 cycle machines. For intermediate capacities, both 60 and 25

cycles, solid discs are used in some cases instead of the plate construction. This brings the larger turbo development up to the present date.

In the comparatively small 60 cycle turbo-generators, where the parallel slot construction with the bronze driving heads was relatively expensive, as already described, the later development has been towards core and shaft forged in one piece, and with

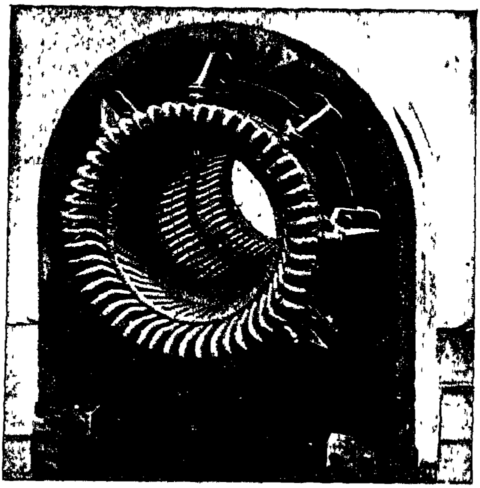


FIG. 29—STATOR OF 625 K.V.A., 2 300 VOLTS, 3 600 R. P. M., TURBO-GENERATOR

With axial ventilation and central duct. Supporting ring both inside and outside the end windings. Typical method of bracing smaller machines.

radial slots, and eventually this construction may be carried up to the largest practicable size of 3 600 r. p. m. machines. It is difficult to predict the limit in capacity which may be reached eventually in 3 600 r. p. m. generators, but 6 250 k.v.a. appears to be practicable.

Some special radial-slot machines had been developed for the New Haven Railroad about 1907. As these machines were designed to deliver 25 cycle single-phase current, and as the pulsating armature reaction of such machines would be relatively high, the rotors were designed with laminated cores, with a view to lessening core losses. The rotors were made of single disc laminations shrunk on the shaft. The discs were provided with radial slots. The construction was very similar to the later radial-slot rotors, except that the rotor end windings were also embedded in slots, and

supported by wedges embedded in the periphery of the core, whereas, in the later radial-slot rotors, the end windings are supported by external rings. These early radial-slot rotors showed very considerable overheating in single-phase operation, and it was found necessary to apply a very complete cage damper embedded in the periphery of the rotor. Later experience showed that the solid-core parallel-slot rotor with an equal damper applied to its surface was just as effective, and many of the later single-phase machines were built in this manner. However, some recent 11 250 k.v.a. single-phase generators are being built of the plate construction already described.

Regulation and Short-Circuit Currents of Turbo-Alternators

Like the ordinary synchronous generator, the modern turbo-alternator is designed with a comparatively high inherent regulation. In fact, in order to avoid excessive short-circuit currents, the inherent regulation must be made comparatively poor by making the armature self-induction as high as practicable. Even under the best condition, such machines are liable to give 12 to 15 times rated current during the first current rush. Furthermore, the solid plates or discs, of which most turbo-rotors are now made, tend to prolong the period of maximum short-circuit current. The consequence of these conditions is a tremendous racking force acting on the end windings during a short-circuit current rush, which tends to distort the winding badly unless it is very strongly braced. The Westinghouse Company encountered such a difficulty on some of their earliest turbo-alternators and there has been a practically continuous development along the lines of more substantial bracing which has kept pace with the increased requirements of the higher speeds and the higher capacities. The bracing used on the modern machines is designed to resist distortion of the end windings, under dead short-circuit, without reactances interposed, and each new size as it is developed is given such a short-circuit test. A 20 000 k.v.a. 60 cycle, 1 800 r. p. m. high voltage alternator was recently subjected to such short-circuit tests at full voltage without injury.

The preceding gives a brief history of the development of the turbo-generator, insofar as carried out by the Westinghouse Company. The General Electric Company went through a correspond-

ing course of development, in general, although not in the specific constructions described, and a number of interesting types or constructions have been brought out. The gradual increase in speed has undoubtedly had much to do with the evolution of their various types, just as in the case of the Westinghouse evolution. One of the most radical steps which the General Electric Company has made in the past few years is in the change from the vertical to the horizontal type of machines. Presumably the very high speeds which later came into use have had much to do with this change. In the earlier turbo-generator practice, the speeds of the General Electric Company's machines were relatively lower than the

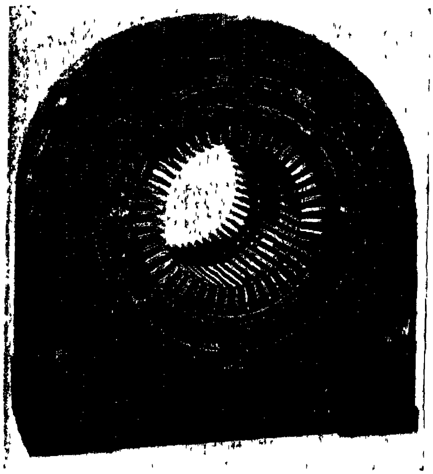


FIG. 30—SAME MACHINE AS SHOWN IN FIG. 29 BEFORE WINDING

Westinghouse, presumably on account of the type of steam turbine used. Many of the early rotor constructions were of the salient pole type for four poles and higher. Gradually these were superseded by constructions leading up to a radial-slot type in which the slots were formed by teeth inserted in dovetail grooves in the rim of the spider. This type was very similar in appearance to the later types, except that the slots had overhanging tooth tips, thus giving a partially closed slot construction. More recently, with greatly increased speeds, this construction has been superseded by solid forged cores with shaft forged on, and with radial grooves milled in the surface for the field winding. These latter rotors are used largely in the horizontal type high speed machines.

In the Allis-Chalmers construction, in the larger machines having four or more poles, the earlier construction of the rotor consisted of forged discs with through shafts. These discs had radial slots for the windings very similar to the present construction of all manufacturers. The smaller machines generally had

FIG. 31—STATOR OF LARGE MODERN TURBO-ALTERNATOR

cores forged in a single piece with the shaft, and with radial windings. As regards methods of ventilation, both the General Electric and Allis-Chalmers Companies went through a course of development leading up to their present practices.

As regards parallel operation, turbo-generators have been particularly free from this old time difficulty, due largely to the uniform rotative effort of the steam turbine, and partly to the high flywheel capacity of the turbo-generator and turbine rotors, which tends to limit any speed oscillations, due to the governors, to a relatively low period, such as would not tend to accentuate the hunting action in the generators themselves. Moreover, in those rotors which have been built with solid cores or of thick plates, the solid material tends to act as a damper circuit. As a consequence, hunting in turbo-generators, or difficulties in parallel running, have been extremely rare.

Induction Turbo-Generators

This type of turbo-generator has been proposed commercially a number of times during the past ten years, and a few installations have been built. The first of any importance, consisting of a 1 250 kilowatt generator of 30 cycles, 1 800 r. p. m., two poles, was installed in the plant of the Baltimore Copper Smelting & Rolling Company. This generator was a true polyphase induction motor, direct connected to a steam turbine. The construction of the generator was exactly the same as would have been used at that time in a two-pole, 1 800 r. p. m. induction motor of the same capacity. The entire load of this machine consisted of a 1 200 kilowatt rotary converter connected directly to the terminals of the generator. The generator and converter were brought up to speed separately and the rotary converter, with its field excited, was connected directly to the generator and furnished the excitation for the generator. There was no other synchronous apparatus in circuit except the converter.

Several years ago, a number of much larger induction generators were built by the General Electric Company for the Interborough Rapid Transit Company of New York City. These machines are of 6 000 k.v.a. nominal capacity and operate in parallel with the 11 000 volt, three-phase, engine-type generators previously installed in the same power house. The engine-type generators furnish the excitation for the induction generators. The entire load of this station is represented by rotary converters. There have been no prominent instances of the use of induction generators for other than steam turbine drive. Apparently this type of generator has no very wide field.

Conclusion

This history is admittedly far from complete, in that it has not mentioned the work of some of the earlier, and also some of the later manufacturing companies. The field is far too large to permit everything to be covered. Moreover, no attempt has been made to describe European constructions and developments in alternating-current generators. It may be stated, however, that in some very important features, European engineers antedated the Americans, while in other equally important constructions American designers were first in the field. As a rule, the representatives of the electrical manufacturing companies have been so

wide awake and ready to adopt new principles when they contained any promise, that it is sometimes very difficult to give any company or individual proper and deserved credit for being first in any given development. Furthermore, no attempt has been made to give credit to the various engineers who have been closely identified with alternator development, for it would be impossible to do justice, or give deserved credit to all of them.

THE DEVELOPMENT OF THE DIRECT-CURRENT GENERATOR IN AMERICA

FOREWORD—This history is not merely a collection of facts or near facts drawn up from old records or from second-hand reports, but is an original story prepared by one who has been in the thick of the battle almost from the early skirmishes, almost thirty years ago. This, therefore, might be called a reminiscence, as well as a history. Being written almost entirely from personal observation and experience, obviously it cannot be considered as a complete history of direct-current generator and motor development, but probably no other individual in the country could write as complete an account of the development, from his own observation and contact with the work itself. This subject, broadly considered, should cover all kinds of direct-current rotating machines, including constant-current arc lighting generators, unipolar generators, etc. However, as the development of the railway motor is to appear in a separate article, and as the constant-current generator has now become commercially obsolete, or practically so, the scope of the following article is limited to the development of the constant-potential generators and motors.

This article was first published in the Electric Journal.—(ED.)

THE history of the direct-current machine goes so far back that it is not within the scope of this paper to cover the earliest developments. Many of the earliest machines were of the constant current type for series arc lighting. Doubtless the peculiar types which appeared in the constant current arc machines impressed themselves upon the early constant potential generators, for these latter were about as numerous in type and construction as the arc machines. One of the characteristic features in the early direct-current design was the radical differences in construction of the machines built by different designers or manufacturers. In fact, every designer appeared desirous of getting out a new type which could bear his name. In consequence freak designs, from the present viewpoint, were much more common than those built upon sensible principles as understood to a limited extent in those days. Real development toward the present almost universal standard types did not take place until the early "cut and try" methods of design were superseded partly, or wholly, by calculations based upon the principles of the electric and magnetic circuits.

Aside from the desire of each particular designer to have his name connected with some new or special type of machine, many

of the freakish characters of these early machines were due primarily to an incomplete or wrong conception of the magnetic circuit. As soon as the magnetic circuit became sufficiently well understood to permit fairly accurate calculations of the magnetic conditions, then the design of direct-current machines began to take a definite trend toward certain constructions. When the "figures" showed that a certain construction was magnetically better, and considerably cheaper, than other known constructions, the manufacturer naturally favored it. In the direct-current machine, as in other types of electrical apparatus, the real development and eventually the standardization of general types was a result of the development of the calculating engineer as distinguished from the experimental and the "cut-and-try" designer.

From the present viewpoint, some very absurd constructions appeared in the early machines. There were some very ponderous arguments put forward for and against such construction, both sides usually being wrong according to our present ideas. For example, the early Edison bipolar field construction used two or more magnet cores attached to each pole piece, each core carrying a field winding. Other manufacturers pointed out the absurdity of such field construction, but as a rule, they did not recognize that they were using, in many cases, similarly absurd magnetic conditions. Two magnet cores per pole piece, or per pole, were found in the "Weston" type, as shown in Fig. 1-*b*, and in the "Brush" or later "Short" type; and each magnet limb carried its own exciting coil, just as in the early Edison machine. This peculiar Edison construction was soon abandoned, while the same feature was retained for some years afterwards by many other manufacturers, while they were still laughing at the Edison absurdity.

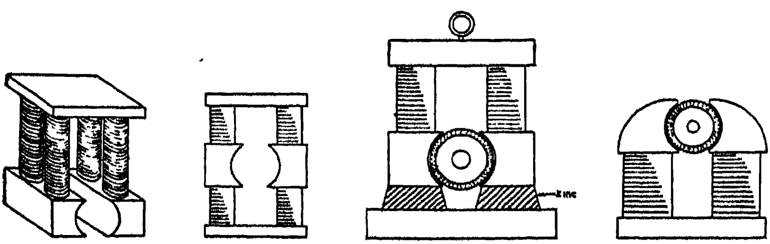
The Bipolar Generator

The first tendency toward any very definite types for general use appeared in railway generators. There were then four leading types of railway equipment, namely, the Edison with the Sprague motor system, the Thomson-Houston, the Westinghouse, and the Short manufactured by the Brush Company. Each of these companies put out its own type of bipolar railway generator.

The Edison railway generator was practically a duplication of the Edison lighting generator. The general arrangement of the magnetic circuit was as shown in Fig. 1-*c*. The field cores, yoke and pole pieces were usually of wrought iron. The construction

was comparatively massive. The armature was of the surface-wound, two-pole "drum" type, and hand wound. On some of the earlier generators, copper brushes were used, but carbon brushes were adopted later. Many of these machines were compound-wound, the same as in present standard railway practice.

Occasionally some very weird engineering was used in the early days in connection with compound windings, when operating two or more machines in parallel. For instance, in one railway plant of about 1889, which the writer examined personally, the machines were properly installed as far as armature and field leads and equalizer leads were concerned, but the main ammeters were connected in the *series coil circuits*, beyond the equalizer leads, so that they indicated the current in the series coils and not in the armature. Moreover, each series field was provided with an adjustable shunt so that the currents of the different series coil circuits could be properly equalized. A very noticeable characteristic of this plant was that some of the armatures heated and sparked



A B C D

FIG. 1—EARLY GENERATOR FRAMES

A—The Edison type. B—The United States (Weston) type. C—Later Edison type, with magnetically insulated base. D—The Thomson-Houston type.

much more than others and had to be rewound frequently, while others never had to be rewound. The engineer in charge was much worried over this situation until the writer, in discussing the installation of a Westinghouse generator in this plant, jokingly asked him whether he wanted the ammeter of the Westinghouse machine placed in the armature circuit, or in the series field circuit. The engineer immediately "saw something," for over night he revised the arrangement of his existing circuits, although the former arrangement was in accordance with the manufacturer's drawings. This case is cited simply as an illustration of the mistakes which were not uncommon in those days, and were not confined to any one manufacturer.

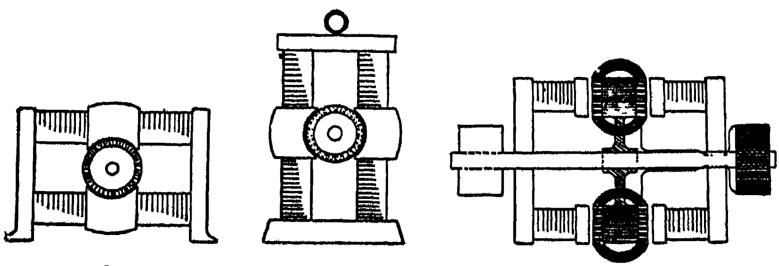
The Edison type of generator had one serious handicap from the magnetic standpoint, namely, the pole pieces had to be insulated magnetically from the bedplate, as indicated in Fig. 1-*c*. This insulation was of some non-magnetic metal, such as zinc or brass. It had to be of considerable thickness to prevent undue shunting of the magnetic field, for this shunt path was in parallel with the air-gap between the armature and field, which was usually quite long, due to the heavy surface windings on the armature core. This Edison type of machine, however, survived in railway work as long as the bipolar type lasted.

One of the early Thomson-Houston constant potential generators was modeled after the characteristic Thomson-Houston arc generator. It had a globular type armature, and the general arrangement of the field type armature, and the general arrangement of the field structure was similar to that of the arc generator. This machine had a demagnetizing or "compensating" coil over the armature, with a view to compensating for armature reaction. Apparently, this machine was used but little, if at all, in railway work. The principal type of Thomson-Houston generator for railway work was practically equivalent to the Edison machine turned upside down, Fig. 1-*d*. One of the best known machines of this type was designated as the "D-62." This had a normal rating of about 80 horse-power, or 60 kilowatts. Magnetically the construction of the machine was superior to the Edison bi-polar, in that the pole pieces, being at the top of the machine, did not have any undue leakage to the supporting parts. The armature of this machine, like the Edison bi-polar, was of the drum type, with the coils wound on the surface by hand. Some of these machines also had "compensating" coils over the armature. This machine was in great repute at one time, and was undoubtedly a good operating machine, for those times. Like the Edison, the Thomson-Houston machine was belt-driven. The writer was much impressed back in the 90's, upon seeing a generating station containing what was said to be 80 of these D-62 machines in one generating room, all belt-driven from a system of line shafting overhead. The forest of belts was exceedingly impressive. Like the Edison, this type of generator persisted as long as bi-polar generators were used in railway work.

A third type of bi-polar generator which was used in the early railway work, was the "Weston" type, built by the United States Electric Co. (controlled by the Westinghouse Electric Co.) Or-

iginally, this type of machine was arranged with horizontal magnets, as indicated in Fig. 2-*a*. In the smaller machines the bearings were carried by bronze brackets connecting the pole pieces. In larger machines, separate pedestals carried the bearings. In the railway generators, most of the machines of this type were arranged with vertical instead of horizontal magnets, as shown in Fig. 2-*b*. Separate pedestals carried the bearings in these vertical machines. Like the Edison and Thomson-Houston machines, above described, this United States machine had a surface-wound, drum type of armature, hand wound. This bi-polar railway machine was used to a less extent than the Edison or Thomson-Houston machines, because the Westinghouse Company did not get into electric work as early as the Edison and Thomson-Houston Companies. However, this type persisted as long as any of the other bi-polars.

A fourth type of bi-polar generator which was used extensively in railway work, was the "Short" generator. This was modeled after the general lines of the Brush arc generator, the Short railway system being manufactured by the Brush Company.



A B C

FIG. 2—EARLY GENERATOR FRAMES

A—The United States (Weston) type, with horizontal magnets. B—The United States (Weston) type, with vertical magnets. C—The Short (Brush) type.

Like the Brush arc machine, the Short railway generator had a ring armature with the armature coils lying between teeth on the two side faces of the armature core, the pole pieces being presented toward the sides of the armature. The armature, therefore, was really of the "disc" type. The field magnets were arranged on each side of the armature, just as in the Brush arc machine. The commutator was placed outside the frame on one end of the shaft and the armature leads were carried down radially from the armature winding to the shaft and along the shaft to the commutator. The whole construction of the armature was very awkward,

from the present viewpoint. The general construction is indicated in Fig. 2-*c*. The armature required a non-magnetic spider as was the case in all bi-polar ring armatures. Possibly one of the worst defects of this type of machine was the liability of a strong side pull due to inequality of air-gaps on the two sides of the ring armature. Any inequality meant an unbalanced magnetic pull with a tendency for an axial movement of the shaft. Thrust bearings were necessary to prevent this. In this machine were evidences of the later slotted armature construction. However, it is questionable whether the armature teeth on these early Short generators were designed primarily for magnetic purposes or for mechanical reasons. They did not constitute a toothed armature, as we design it nowadays. However, the machine must have acted, to a certain extent, as a toothed type. Like all the others, this machine was belt-driven. It also persisted as long as the bi-polar machines were used for railway service.

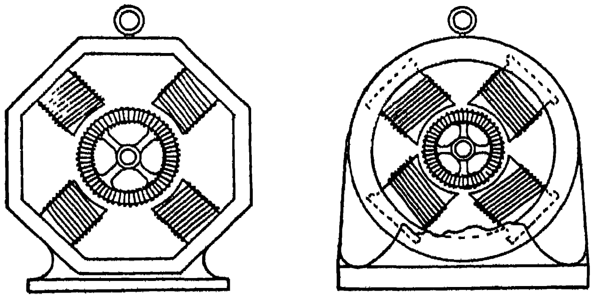
From the above it may be seen that all of the leading bi-polar railway generators were quite different from each other in their general appearance and construction. There were many warm discussions regarding the merits and demerits of each type. When equipped with carbon brushes, all of them operated reasonably well. All of them ran rather hot in the armature, due to the fact that little provision was made for ventilation. In this respect the Short armature was probably better than the others, as it was of a fairly open ring construction. Being surface-wound in practically all cases, the commutation was not difficult, as the self-induction was low. When the multi-polar types of railway generators came in, there were lots of "stand-patters" who insisted that the old two-pole machines were good enough, and that we were foolish in trying to do away with them.

In these various types of bi-polar generators, the Edison was carried up to 150 kw capacity, or possibly somewhat larger; the United States was carried up to 150 kw capacity. Apparently the Short and Thomson-Houston were not carried up to such large sizes, the Thomson-Houston "D-62" being the "crack" machine, to the end of the bi-polar dynasty.

There were a number of other railway generators at this time in this country, but they were not as well known as the above and did not persist as long, presumably because the railway systems of which they usually formed a part, did not persist.

Multipolar Types

About 1890, the Thomson-Houston Company, in bringing out a larger capacity railway generator, adopted a multipolar design, in which an external octagonal-shaped yoke supported four internally projecting poles, each of which carried a field winding. This arrangement, shown in Fig. 3-*a*, was thus an approach to the present almost universal type of field construction. The armature was of the ring type, with four circuits, one per pole, and there were four brush arms and four sets of brushes on the commutator. This machine was separately excited, an exciter being provided. The opinion was somehow spread broadcast that separate excitation was necessary in general, and for parallel operation in particular, in multipolar generators. No real explanation was forthcoming as to why this was so, but apparently almost everybody accepted it as a fact without explanation. Shortly after the introduction of this multipolar type of generator, the writer examined several such machines which had just been installed in the Duquesne Traction power house in Pittsburgh. The conclusion



A B

FIG. 3—EARLY MULTIPOLAR GENERATORS
A—Octagonal frame. B—Cylindrical frame.

drawn was that separate excitation was necessary only because the machines were not worked sufficiently high on the saturation curve to give stability when self-excited. With the surface-wound armatures and consequent large air-gap, together with the multipolar construction, a relatively low saturation was used apparently. Possibly the writer drew a wrong conclusion in this case, but nevertheless he made up his mind that self-excitation was just as practicable in multipolar railway generators as in bi-polar.

As stated before, the United States bi-polar machines were furnished by the Westinghouse Company for railway work. These were built at the United States Works at Newark, New Jersey. But early in 1890, the Westinghouse Company considered the construction of larger generators at its Pittsburgh shops, and a contract was taken for a 250 horse-power generator for railway work. The electrical design for this machine was prepared by the writer. A cylindrical external field with inwardly projecting poles, as shown in Fig. 3-*b*, similar to the Westinghouse alternators of that time, was chosen as the ideal type. The four poles were *laminated* and were cast into the yoke similarly to the Westinghouse laminated field alternators of that date. This field was also a close approach to the present standard construction, being a slight step ahead of the Thomson-Houston machine described above, in the use of laminated poles. The armature was of the ring type, surface-wound. At this time the air was filled with talk that the ring armature was the coming type. There were some good reasons for this. In the older bi-polar drum armatures, most of the over-heating had been in the piled up, unventilated end windings. As the ring armature had no end windings to speak of, it was naturally supposed that all troubles from heating would be overcome by the adoption of this type. Thus the last weak point in the railway armature was supposed to be done away with.

Being convinced that multipolar generators would operate satisfactorily when self-excited, if worked high enough on the saturation curve to give stability in excitation, the writer deliberately designed this first four-pole machine for self-excitation, but this was not known to anyone but the Company's superintendent Mr. Albert Schmid, who was fully in accord on this point. However, when the machine was about completed and ready for test, the information leaked out that it had been designed for self-excitation, which, of course, was entirely contrary to all good and accepted practice. The writer was criticised from all sides for his temerity and for his lack of good judgment. However, the machine was put on test, and did operate in an entirely satisfactory manner when self-excited. But some of the wise ones still shook their heads, for we were violating all known "laws." Nevertheless, we stuck to self-excitation, and it is still with us.

When testing this first machine, considerable new experience was obtained. For instance, when running at normal voltage,

the machine was dead short-circuited across the outside terminals with a somewhat surprising display of fire-works. Also when, after this short-circuit test, the surface-wound ring-armature winding was found to be shifted about two inches circumferentially at certain points, some of us had doubts regarding the desirability of this type of winding. This was one of the points that led to the slotted armature construction described later.

This first Westinghouse multipolar machine was considered a "giant," and railway people all over the country were invited to witness its operation in the Company's Pittsburgh works. Quite a number of visitors did come long distances to see this 250 h.p. machine, and some comments were made that this was probably the upper limit in size that would ever be made. It was, at that time, hard to conceive that any electric railway would ever need anything larger than this capacity. Moreover, it was thought by some that the limit in belting had been reached. As everything was belted in those days, it was difficult to see that any other method of drive was possible. Nevertheless, this machine was quite a wonder, compared with what had preceded it.

Slotted Armature Types.

Several machines of this type and capacity were built and put out. However, the writer was not entirely satisfied with the ring winding in particular, nor the surface winding in general. At this time, in alternating-current work, there was a strong tendency toward "toothed" armature constructions, with the windings completely embedded below the surface of the core. These alternating-current armature types with one tooth per pole did not lend themselves to direct-current work, but the idea of embedding the windings persisted. In the summer of 1890, while scheming on a new railway motor, a slotted armature construction was worked out by the writer, with a view to improving the magnetic conditions so greatly that a slow-speed single-reduction railway motor would be possible. The calculations for the magnetic condition (crude as they were in those days) showed such astonishingly good results that the same construction was considered in connection with the design of a large Westinghouse slotted armature railway generator which in many ways may be considered the forerunner of present practice. These calculations on the railway motor resulted in the well known Westinghouse No. 3 single reduction motor, which was practically the forefather of the present uni-

versal type of railway motor. This was not actually the first single reduction motor, but was the first which anyways nearly approached the present type.

It was while making the original calculations on the slotted armature for the single reduction motor that the "two-circuit" or "series" type of armature winding was devised for multipolar machines. In working out the railway motor, it soon became evident that a four-pole design was necessary. With any of the then known armature windings, either four-brush arms were required on the commutator, or the commutator had to be cross-connected at every bar, in order to allow the use of two-brush arms only. The writer deliberately set about to devise an arrangement of connections which would allow the use of two-brush arms on a multipolar winding without any other cross connections than the normal connections of the winding. The two-circuit winding was the result, and the law of the winding was worked out for various combinations of poles, etc., while still closing on itself properly. This winding was included in the design of the trial single reduction motor then being designed. Question was raised regarding this new winding, when it was first proposed, by those who appreciated that something radically new was involved in its use. The writer had to "swear up and down" that it was absolutely correct in principle, even if it was new and untried, but he apparently convinced the others more by his vehemence than by his theories, for most people in those days had very little conception of the theory of armature windings. However, when the first single reduction railway motor armature came on test, the theory proved to be all right—at least the armature was all right and had but two brush arms on a four-pole machine. This, as far as the writer knows, was the original two-circuit multipolar winding in this country. Application for a patent was refused however, on the basis of a certain, until then unknown, foreign patent—that is, unknown as far as the writer and any of his colleagues were concerned. It may be worth mentioning that at the time this two-circuit winding was first used, the criticism brought against it was that it was entirely too complicated to be adopted generally. This is interesting in view of the fact that at the present time this is our simplest direct-current winding, and it is used probably to a greater extent than all other windings together. Prophecies in those days were no more reliable than they are at present.

Returning to the slotted type of railway generators, as stated above, it was decided to build an armature of this type. Slotted armatures had previously been used in America by the United States Company and others on comparatively small capacity generators and motors, but apparently on nothing "within gunshot" of the size which we were contemplating. Therefore, opinions were obtained from a number of then eminent engineers who had had experience of some sort with slotted armatures. All opinions were unanimous that we could not make a 250 horse-power railway armature of the slotted type which could commutate successfully without rocking the brushes with change in load. This was very discouraging, but it was then decided that this was possibly a case where everyone was wrong, and that we had better build one armature in order to obtain some positive information.

This new railway armature was designed with 95 slots and 95 turns and 95 *effective* commutator bars, the new two-circuit drum winding being used, although it was intended that there should be four brush arms. As 95 turns were all that could be used, with the desired saturation of the existing field frame, and as there did not seem to be enough bars for a four-pole, 525 volt machine, the actual number of commutator bars was made 190, but only every other bar was connected to the armature winding. The intervening bars were idle (or "dummies"), and really constituted broad insulating or separating segments between the active bars. The brushes covered practically four bars, so that they touched two active bars all the time.

There was considerable discussion regarding the type of armature slot to be used, namely, whether it should be partially opened at the top or should be entirely closed. It was finally decided to make the slots entirely closed, on the principle that the closed slot would be the ideal one if it prove satisfactory, and if it didn't prove satisfactory, the slots could then have openings cut in the top, without rewinding.

When this first machine came on test, some most remarkable results were obtained, due apparently to both the idle segments in the commutator and the entirely closed armature slots. Sparking was present at all times, even with only the exciting current as a load. Rocking the brushes was tried for curing this, but when any considerable load was carried no point of sparkless commutation could be found. However, a curious feature of the results was that the brushes could be rocked *practically anywhere on the com-*

mutator without causing flashing. Copper brushes were tried with like results. Also, copper brushes were tried behind the carbon brushes, and, in some cases, such heavy local currents were generated between the copper and carbon brushes that the brushes got red hot over almost their full length, and yet we did not produce a single flash from this machine, although we explored around over almost the entire commutator with the experimental brushes. Mr. Chas. F. Scott and the writer spent almost an entire night experimenting with the brushes and brush-holders, with our faces at times almost against the commutator and brushes, where a flash would probably have caused permanent injury to us. In view of the vicious flashing which occured at times on later machines, it is still somewhat of a puzzle why this first machine was so absolutely non-flashable. Apparently, the "dummy" commutator bars should receive most of the credit for this result.

Finding that the closed slot construction was a failure, the armature slots were then cut open as wide as possible while still retaining sufficient overhanging tips for holding the armature conductors in place. The first test after this showed a marvelous improvement. The armature now would carry from no-load up to considerably above its rated load without serious sparking and without shifting the brushes. The machine was then put on exhibition and many prominent people saw it put through its "stunts." The only serious defect that developed was in slight spotting or burning of alternate commutator bars. In an attempt to overcome this, each idle bar was connected to an adjacent active bar, thus reducing the total number of bars to 95. Under this condition the spotting was stopped, and the commutation appeared to be just as good as before; therefore it was decided that 95 bars were sufficient for a four-pole, 525 volt railway generator of this general construction.

This slotted armature railway generator turned all future construction of large machines toward the slotted type. However, this first machine by no means fixed the final design of this type of armature, but merely set the general type. Many variations appeared in the following years, but all contained the slotted construction and the drum type of armature winding. As far as the armature itself was concerned, the principal variations were in the shape of the armature slots and in the form or construction of the armature coils. Furthermore, some experience was required in order to determine the best proportions of armature teeth, air-gap,

etc., in order to produce good commutation over a wide range of load without brush shifting, a very necessary condition in railway work. While in fact this first large generator did not require brush shifting, yet the reasons for this were not fully appreciated at the time, and therefore the good results obtained were, to a certain extent, accidental. The right conditions were aimed at in making up the design, but as it was largely a question of how far to carry certain proportions, it was partly accidental that these conditions were carried just far enough to obtain such satisfactory results. In this first machine the armature teeth were made comparatively thin and short and were saturated to an excessive degree. Also, the air-gap was purposely made quite large, with the idea that the air-gap and tooth saturation together would require very high magnetizing ampere-turns compared with the armature ampere-turns, which was considered as a very desirable condition for commutation. However, the extremely beneficial effect of high tooth saturation in holding the brush lead constant was not then fully appreciated. This was discovered when a somewhat larger machine was built a few months later. In this larger machine the tooth saturation was considerably lower than in the first armature, although the air-gap ampere-turns were comparatively high. This later machine was found to be much more sensitive to shifting of lead than the former machine. A careful study was made of the influence of tooth saturation in holding the lead constant, and from this study a scheme for saturating the pole face instead of the armature teeth was suggested, which will be referred to later. The Thomson-Houston earliest slotted type railway generators were also subject to change in lead, but evidently the cause of the difficulty was soon discovered, for the later machines were not so sensitive in this regard. Also, apparently their earlier slotted machines had weaker fields compared with the armatures than was the case with the Westinghouse machines.

The early Westinghouse slotted armatures for railway generators all had partially closed slots, while some of the early Thomson-Houston machines had rectangular open slots and others had partially closed slots. The slot construction depended, to a certain extent, upon the the type of armature winding used. The early Westinghouse machine had only two round conductors per slot, which were threaded through two stout insulating tubes made of rolled up paper and shellac, as shown in Fig. 4-*a*. These tubes had walls of 1-16 to 3-32 of an inch in thickness. The winding

consisted of either round solid conductors or of twisted cable, threaded through these tubes. The conductors were first cut in lengths corresponding to one complete turn. All the conductors of the lower layer were threaded through the lower tubes and then bent down at each end in an involute shape, as indicated in Fig. 4-*b* and *c*. At the front, or commutator end, the conductors extended just sufficiently to furnish the front end connection to the commutator. At the rear end, the conductors extended far enough to furnish the return or upper layer. The lower layer, after being bent down at each end to an insulated support over the shaft, was banded or clamped down solidly to the support. The extended rear ends of the coils or conductors were then bent outward to the periphery of the core, in an involute form and were shoved through the upper layer of tubes, and carried directly to the commutator,

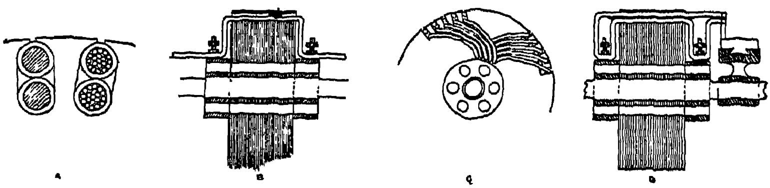


FIG. 4—EARLY WINDING SCHEMES

thus completing the winding. The various steps in this construction are indicated in Fig. 4-*d*. In the smaller machines, that is, from about 150 kw down, solid conductors were used, these being in some cases as large as No. 2 B.& S. gauge wire. The maximum size of solid conductor was determined by the ability of the winders to handle it without undue difficulty. For larger sizes, twisted cables were used, made up of fairly large wires, such as No. 10 or No. 12 B. and S. gauge. Considerable stiffness was preferred in order to give mechanical strength to the winding. This type of armature winding was used for a number of years, and was sometimes modified to the extent of four, or even six tubes and conductors per slot, arranged radially. Also, in some cases, the section of the tubes was made elongated to take two or three parallel conductors forming one turn. In the larger machines with this winding, with the very high tooth inductions used, undoubtedly the use of cable materially lessened eddy currents in the conductors. This, however, was not a prime reason for the use of cable, ease of winding being the principal reason.

Some of the early Thomson-Houston slotted armatures had open slots, while others had partially closed slots, of rectangular shape in both cases. Straight copper straps or bars of rectangular section were either laid in or shoved through the slots from one end, depending upon whether the slots were of the open or partially closed type. Separate strap end connectors of the involute type were riveted or soldered to the armature bars at each end. This general construction is shown in Fig. 5-*a*. The writer does not know whether this was the earliest Thomson-Houston winding for slotted armature generators, but it was, at least, a very early one. In some cases, two or even three bars were placed side by side in one slot, forming two or three separate turns. This general type of winding was retained by the Thomson-Houston Company (G. E.) for several years.

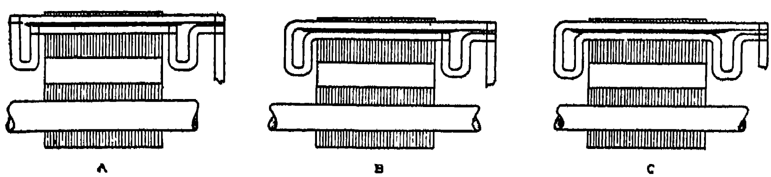


FIG. 5—EARLY COIL FORMS

Formed Coils

After two or three years' use of the Westinghouse "shoved-through" type of armature winding above described, the development of a type of armature coil, which could be completely formed and insulated before placing in the slots, was taken up. Various schemes to accomplish this were undertaken. The first one attempted consisted in forming the rear end and the two straight parts of the coil as a complete coil which was then shoved through the partially closed slots from the rear end, the front end connectors being formed of copper strap which were then riveted or soldered on, after the conductors had been shoved through the slots, as shown in Fig. 5-*b*. One armature of the sort was actually constructed. It was appreciated however that if open armature slots were used, instead of partially closed, the entire coil, including both front and rear end connections, could be constructed in one piece. This construction was then tried out and adopted, as illustrated in Fig. 5-*c*. It may be noted that both end windings, in this early one piece coil, were of the involute type. This construction was retained by the Westinghouse Company for some years, and was extended to two, three, and even four and five,

separate conductors side by side in one slot. Then gradually the involute winding at the front end was replaced by axially arranged end windings between the armature core and commutator, just as in present practice. The rear end was later straightened up in the same way, so that the present type of winding was thus attained.

Incidentally, it should be mentioned that the completely wound coil, with involute end connections, was developed and applied by Rudolph Eickemeyer, to surface-wound armatures, several years previous to this. In this, as in several other things, Eickemeyer was considerably in advance of his time. In some of the earlier armatures with open slots, the windings embedded in the armature core were supported by bands over the core. This appeared to be the usual Thomson-Houston practice, (some of the above developments occurring during the formation of the General Electric Company from the Thomson-Houston and Edison Companies). With open slots, the preferred Westinghouse construction consisted of fiber wedges over the embedded parts of the winding, but the writer does not know whether this construction originated with the Westinghouse Company or not. There was considerable discussion as to the relative merits of the two arrangements, but apparently both were entirely successful.

End Winding Supports

As regards supports for the end winding, the early shoved-through winding on the Westinghouse machines, shown in Figs. 4-*b* and *c* had good supports at each end against centrifugal force. The slots being partly closed, this type of winding therefore had no bands or wedges on any part of it. With the development of the strap coil, as shown in Fig. 5-*c*, it soon developed that in high-speed machines the rear end of the winding required some sort of support. This was first made in the form of bronze end bells, which braced the end winding, both axially and radially, as shown in Fig. 6. The front end winding had no support. However, in the early years of this winding, very low speed armatures were the rule, for this was the age of engine-type generators, which will be referred to more fully. Except in rare cases, the armature end connections were rigid enough to be self-supporting without belts or bands. When rotary converters and motor-generators came into general use, with their very much higher peripheral speeds, the end bell over the rear end was eventually replaced by axial end windings with heavy bands, as in

present practice. The Thomson-Houston or General Electric Company preceded the Westinghouse Company in the use of bands on the end windings, probably in part because their built-up end windings had more need for some external support. Also, as they abandoned the built-up end construction in favor of complete coils, they changed to the axial construction on the rear end, which also necessitated the use of bands. Thus both companies eventually came to the same construction, through different courses of development.

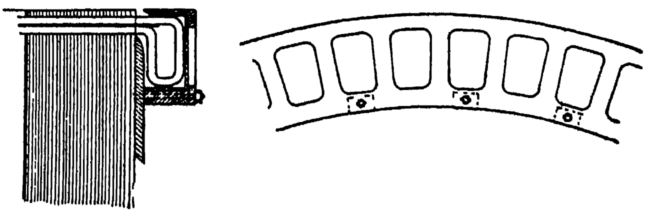


FIG. 6—METHOD OF BRACING THE END WINDINGS BY A METALLIC END BELL

The writer has gone into this history of the slotted construction and the armature windings, because these constitute probably the most radical points in the history of direct-current generator design.

Other Multipolar Types

Something should be said regarding other types of multipolar generators developed during this time. The Edison Company did not go into the multipolar design for railway generators, as far as the writer knows, for about this time, the Thomson-Houston and Edison Companies were combined into the G. E. Company. The Edison Company, however, had designed and built some large low-voltage generators for the Edison licensee companies. These had large cylindrical external fields with inwardly projecting poles of cast steel or wrought iron. The armatures were of the ring type, surface wound, and were fitted with radial commutators on one face of the armature core, the commutator bars forming part of the armature winding. These machines, as a rule, used metal brushes. They were manufactured up to quite large capacities by the General Electric Company in continuing the Edison design.

The Short bi-polar type of railway generator was simply expanded into a multipolar type, having the same general con-

structional features. This apparently presented no advantage over the Short bi-polar machine, except that it permitted machines of larger capacity to be built. At one time it was claimed by some authorities that the Short multipolar generator was the coming type. However, it was apparently too expensive, for later, in organizing the electrical work of the Walker Company, Prof Short abandoned this construction in favor of one similar to the Westinghouse and G. E. machines.

Engine-Type Generators

All the earlier generators were of the belted type. This was eventually carried up to comparatively large capacities in either belt or rope drive, 500 kw machines being not uncommon. However, shortly after the slotted type of armature construction came into general use, a tendency was manifested toward direct driving from the engine. Once well started, direct driving soon became almost exclusive practice, except for extremely small units. Two methods of direct driving were used about equally in the earlier practice, namely, direct coupling of complete generator units to the engines, and straight engine-type machines in which the generator armature was placed on the engine shaft. The former might be said to be an adaptation of the belted type to direct driving. The engine-type machine, however, might be considered a distinct type, as the units were designed primarily in connection with the prime movers.

Designers of direct-current machines rather welcomed the engine type, even if it did make much of their former work obsolete, for the engine-type machine very much simplified some of the problems which had been encountered in the larger capacity belted machines. For example, the commutation problem became very much easier, due to the much lower speed, larger commutators, etc. The heating problem was also temporarily solved, for the engine-type machines were comparatively large and massive for a given output, and thus could dissipate their heat rather easily.

The direct-coupled and engine-type practice, once started, came in rather quickly. The first railway units appeared about 1892, and by 1893 they had made great progress commercially. A number of large engine-type and direct-coupled railway generators were exhibited by various manufacturers at the Chicago Worlds Fair in 1893. The power house for the Intramural Rail-

way at the Fair contained practically only such machines, if the writer remembers rightly. The Worlds Fair engine-type generators were presumably all exhibition machines; however, they were but little, if any, ahead of the times for, during the same year both the Westinghouse and G. E. Companies contracted for a number of very large machines of the engine type. It might be said therefore that the engine-type railway generator was well established commercially, in 1893, or within about two years after the first slotted armature for large railway generators was developed. Without the slotted construction, it is doubtful whether such rapid and enormous development could have taken place.

There was one exception to the slotted armature construction in large machines for railway work, namely, the Siemens-Halske generator, which was exploited in this country for several years from about 1895. This was the well-known external armature construction, in which a ring wound armature surrounded a stationary multipolar internal field structure. The armature was ring-wound, the inner surface cutting the field, while the outer surface formed the commutator. The brushholder thus surrounded the entire armature. When first introduced into America, these generators used metal brushes, this being possible due to the surface type of winding, low voltage per bar, wide neutral zone, etc. However, in American railway practice, metal brushes did not prove entirely satisfactory, especially in case of short-circuit, as they burned, and burred and "welded" badly. Carbon brushes were used later, but the general construction was not very suitable for such brushes. This type of machine as a whole was not competitive with the rugged, well-protected armature and commutator construction of other American makes, and it dropped out when the American Siemens-Halske Company went out of business. It is interesting, however, as a late survivor of the surface-wound type of railway generator armature.

The engine-type construction in general soon spread into all fields of electric generator work, such as lighting, electrolytic work, etc., and was a standard construction for many years, before it suffered a decline. In small lighting work, the type persists today, but has now almost disappeared in railway work, due largely to the general introduction of the polyphase alternating-current system of generation and transmission of power, with conversion to direct current by rotary converters and motor-generators. The period of decline began about 1898 to 1900, when large capacity rotary converters began to take the field.

When the engine-type practice was in vogue, some very large units were constructed for comparatively low speeds—1 000, 1 500 and 2 000 kw units at 75 to 80 r. p. m. were common, and quite a number of railway units of 3 000 kw were built. For lighting service, some units of still larger capacity were built.

The engine type machine in its prime was a magnificient piece of apparatus. On account of its low speed, it was of comparatively large dimensions for a given output. In the largest capacity, low-speed engine-type generators, overall dimensions of 25 to 27 feet were attained. This is very large, compared with present practice. which is confined almost entirely to relatively high-speed machines However, large as they were, they were midgets, both in size and capacity, alongside some of the alternating-current engine-type generators at their maximum. The latter were constructed up to capacities of 5 000 to 6 000 kw compared with 3000 kw for direct current, while the engine-type alternators attained overall diameters as high as 42 feet. Incidentally, as regards capacity alone, the race between alternators and direct-current machines has been very much one-sided, almost since the polyphase system became thoroughly commercial, the earliest Niagara generators (constructed in 1893), of 3 750 kw, being practically of as large capacity as the largest direct-current machine ever built; while in later polyphase work, generators of the usual multipolar construction have been built up to 17 000 kw, and turbo-generators up to 30 000 and 35,000 kw. Obviously, as regards maximum capacity, the direct-current machine makes but a poor comparison, for reasons which do not come within the scope of this paper. Nevertheless, this should in nowise detract from the direct-current generator, as an engineering accomplishment.

In general, the engine-type constructions of different manufacturers were very similar, except in details. The principal differences were in the way the field yoke was split, in the construction of the field poles and field winding, and in the details of the armature winding, as already described. In the earlier Westinghouse machines, the field yoke was split vertically, so that the two halves could be moved away from the armature in a direction at right angles to the shaft. The G. E. construction, in general, was horizontally split, and access to the armature was obtained either by sliding the field parallel to the shaft or by removing field poles or by lifting off the top half of the field. There was much argument regarding the respective merits of these two constructions.

Field Poles and Windings

On the subject of field poles and field windings, something may be said, because this part of the direct-current machine underwent many modifications in type, materials, etc. In the early bi-polar machines already described, the pole pieces and poles varied with the different types. The Edison and T-H constructions used wrought iron or cast steel in both the poles and yoke, as far as the writer knows. The field cores in the Short machines were of wrought iron or cast steel, and presumably similar material was used in the pole pieces. All these machines had cylindrical magnet cores with cylindrical field coils surrounding them. The United States (Westinghouse) bi-polar machine had cast iron fields throughout. The magnet cores were oval in shape instead of circular.

When the multipolar generators came in, various constructions of poles and pole pieces were used by different manufacturers. The Westinghouse Company used poles of rectangular shape, of laminated steel, which were cast into the yoke. The field coils were of rectangular shape and were slipped over the poles from the air-gap end. The rectangular shape of magnet core and the laminated construction has been retained throughout by the Westinghouse Company in their multipolar generators, except in some early, relatively small capacity belted and engine-type generators, in which cast-iron poles were cast integral with the yoke. These also were rectangular in shape.

Many of the other manufacturing companies, in their early multipolar machines, used wrought iron and steel very extensively in the magnet cores and pole pieces and, in some cases, in the yoke. Frequently the magnet cores were made cylindrical, while the pole pieces or caps were rectangular. The theory was that the cylindrical core was the most economical shape for both iron and copper. This of course, was true where the armature diameter was the limiting dimension in the machine and where, in consequence, there was plenty of field space for use of the cylindrical poles. For a given section of field iron, obviously the cylindrical type of core and winding required more room circumferentially around the armature, than rectangular poles of equivalent section.

The solid pole face was not very objectionable on the early machines, especially where the air-gaps were large, and the armature slots were relatively narrow. However, the tendency of design was toward wider armature slots with several bars side by side in each slot, as this allowed considerable increase in capacity for a

given armature diameter, and also the wider slot permitted better commutating conditions. Also, especially in engine-type machines with many poles, the design tended towards smaller air-gaps Consequently, conditions were soon reached where there was considerable "bunching" of the magnetic flux in the pole faces, due to the relatively wide armature slots. This meant loss and heating in solid pole faces, especially under flux distortion with load. With laminated poles, this heating was apparently very small, but with solid poles it was sometimes excessive—so much so that, in some cases, the manufacturers of machines with such solid pole tips would turn circumferential grooves in the pole faces to "semi-laminate" them In some cases, solid magnet cores were used with laminated pole tips. The Bullock Company, like the Westinghouse, used laminated poles, but its successor, the Allis-Chalmers Company, adopted solid poles in some of its large machines, but eventually returned to the laminated construction. The T-H Company and later the G. E. Company used solid poles and pole tips for many years. In many cases, however, their magnet cores were rectangular in shape just as in present practice. Unlike the early Westinghouse machines, the G. E. poles were bolted to the yoke which was sometimes of cast steel and at other times of cast iron, while the early Westinghouse poles were laminated and cast into the yoke, as already described, the yoke being cast iron. Thus, both constructions contained some of the elements of present standard practice, which embodies laminated poles of rectangular section, bolted to either cast iron or cast steel yokes.

In the earlier generators, the Crocker-Wheeler Company used cylindrical poles with solid pole tips, but with somewhat larger air-gap than used by other manufacturers, thus avoiding, to a considerable extent, any undue losses in the pole faces.

Field Windings

The construction of field windings is so closely related to that of the pole pieces that a brief account of their development may be given at this point. Practically all the early field coils were wound in metal bobbins or shells. They were usually very heavily insulated, both inside and outside. The metal shells were first lined with paper or other insulation to a considerable thickness; the wire was then wound in, usually with much paper or cloth between the layers, and then the outside surface was covered possibly ¼ in. deep with a finishing layer of rope. The whole construction was a most excellent one for keeping in the

heat. If a coil ran too hot, more copper and insulation were added, instead of improving the heat dissipating and ventilating conditions. Naturally, in following such lines, the field coils eventually became very massive. Shunt field coils on railway generators were not infrequently four or five inches deep. When one of these coils roasted out it was usually found that the first half inch of wire next to any heat-dissipating surfaces was usually in fair condition, while deeper in the winding was progressively worse. To overcome this, in some cases the field coils were made in two concentric parts with a narrow space between. This was the first step towards improving the ventilation.

In the construction of the early field coils, the writer objected often, and strenuously, to the enormous amount of insulation embedded between layers in such coils, and also to the great depth of insulation in the metal shells. This great depth in the shells was due largely to the fact that the various parts of the insulation were "butted" instead of being overlapped, so that great thickness was required to give sufficient creepage distance One early improvement was in the use of overlapped insulation at the joints, which allowed a great reduction in thickness. Also, the introduction of coils without metal shells, which followed from the use of similar coils by the Westinghouse Company in railway motors, allowed the outside surfaces to be insulated after the coil was completed. This was another step in the direction of reduced insulation, for this type of coil could be insulated more satisfactorily and with less danger of bad joints, than when the shells were used. But still enormous quantities of insulation were used between layers. The writer arranged a "horrible example" of this one day when tearing down a large field coil. The insulation between layers was carefully piled up as the coil was unwound, until, at the finish, the pile of insulation from the inside of the coil was several times larger than the original coil, due of course to being loosely piled. But it was hardly believable to the observer, that all that "stuff" came from the inside of the coil. Gradually, however, it was found that much of this internal insulation could be omitted. Its only use originally was to prevent short-circuits between layers while winding the coil, as the wire was hammered pretty hard while winding, in order to take out the "bulge."

In series field coils, originally the Westinghouse Company used round wire for the winding, and as the size of machines increased, two or more wires, or two or more field coils, were paral-

leled. In all cases the series winding was placed beside the shunt winding, and generally next the yoke in the earlier machines. Later, strap, wound flatwise, was used in some cases; but about 1895 the strap on edge alternator field winding was developed, and almost immediately the Westinghouse Company used this same winding for series field coils. Incidentally, it may be mentioned that the writer applied for a patent on this edge-wound field coil construction but, to his surprise, found that it had been covered by a patent about 50 years before, in connection with electro-magnets.

In the earlier Thomson-Houston (and G. E.) machines, the field coils were wound in metal bobbins, and this construction was retained somewhat longer than by the Westinghouse Company. In many cases the series winding consisted of strap or ribbon wound flatwise, outside the shunt winding. The merits of this construction, compared with the strap-on-edge, were much discussed, but apparently both were sufficiently good constructions for those times.

As heat-conducting and radiating conditions and ventilation became better understood, the outer insulation on the coils was reduced materially, and precautions were taken to ventilate the field windings more thoroughly. Series windings were better exposed to the air, and shunt windings were, in some cases, subdivided in order to increase the effective ventilating surfaces. Also, in view of the fact that, with heavy deep coils, the center portion would be roasted out, while the outside part would be comparatively good, practice gradually tended toward comparatively shallow coils, arranged for good air circulation over them. In series coils and in commutating-pole windings, where comparatively heavy strap or bar conductors are used, the individual turns are now separated by air spaces in many cases. In other words, in modern design, low temperatures are obtained not by piling on material, but by improvements in heat dissipation.

Commutation

The problem of commutation and the conditions which influenced it were of paramount importance in the early days. The theory of commutation was understood crudely, and the conditions which gave good commutation were more or less appreciated. It was known that a surface-wound armature should commutate better than the slotted type, with the same number of turns per com-

mutated coil, and with the same current per coil. It was well understood that embedding the coil in the slot would increase the self-induction, and thus render commutation more difficult. The advantages of the slotted construction were pretty well appreciated before its adoption, but everybody feared the commutation. It was not appreciated that, in adopting the slotted construction, the number of armature turns in general, and the number of turns in series per coil in particular, could be reduced sufficiently to overcome the inherently higher self-induction of the slotted construction. As soon as the slotted construction proved practicable in large machines, a new era began in the commutating problem. Designers studied and analyzed the commutating conditions and limitations much more closely than ever before, and many tests were made solely for the purpose of getting commutation data. In this study it was soon determined that high saturation of the armature teeth was beneficial in maintaining a fixed lead at the brushes. At that time, in preparing a brief written analysis of commutating conditions in slotted machines for Mr. Albert Schmid, then superintendent of the Westinghouse Company, the writer showed the beneficial effects of high armature-tooth saturation and explained the reason why this was so, as well as the theories of that time would permit, and he furthermore showed that saturation of the pole face in general, and the pole corners or edges in particular, should accomplish similar results. For then apparently good reasons (but which afterward proved to be entirely wrong) it was decided that it was not worth while trying for a patent. A year later, however, Mr. N. W. Storer applied for and obtained a patent covering cutting away part of the laminations in the field pole corners in order to produce high saturation. Mr. Wm. Cooper (formerly with the Bullock Company, and afterward with the Westinghouse Company), also obtained a patent on cutting away the laminations across the whole pole face. These two patents led into certain expensive lawsuits, but both arrangements were considerably antedated by the author's written analysis referred to above.

The advantages of a "stiff" field in preventing shifting of the armature neutral point was known comparatively early. With the big air-gaps on the surface-wound machines, there was not much difficulty in getting the field ampere-turns, or field strength, much higher than that of the armature. But with the adoption of the slotted armature construction, there was an immediate tendency

toward reduction of the air-gap in order to obtain more economical designs. Experience soon indicated that it was much more economical to obtain a "stiff" field by saturating the armature teeth or the field pole tips or pole face, than by putting the excitation in the air-gap alone. Thus saturation in the path of the armature cross ampere-turns soon became the regular practice. Saturating the armature teeth meant more slot or copper space, but meant higher iron losses. Saturating the pole face or pole corners gave much lower iron losses, but slightly less copper space and copper. However, in general, saturating the pole corners appeared to give better all around results, and this method eventually became standard practice with practically all manufacturing companies.

Another important condition in the problem of commutation was the armature self-induction. In the early days much was talked and written about mutual induction in commutation After the advent of the slotted construction experience soon began to point out that the important factor in limiting commutation was the self-induction of the individual coils, rather than their mutual induction. Therefore, slot construction soon tended toward lower self-induction, that is, toward wide slots. At first, on account of the imaginary large effect of mutual induction, it was not considered advisable to place two or more separate coils in one slot, and therefore a large number of comparatively narrow slots, corresponding to the number of commutator bars, was common. However, with the recognition of self-induction, and not mutual induction, as the controlling factor, practice soon tended toward two and three coils per slot, with correspondingly fewer slots and relatively better slot proportions. The results in general were favorable, and at the same time, with fewer slots and more conductors per slot, the total insulation space was decreased and the copper space was correspondingly increased. This was one of the really big steps in increasing the capacity and decreasing the dimensions of generators. However, like many other good things, this had to be carried too far before the best proportions could be found, and in quite a number of cases too few slots and too many bars per slot were tried, resulting in special commutating troubles, due to improper magnetic conditions.

In working over the problem of reducing the self-induction, the writer conceived the idea of purposely so arranging the armature winding that the upper and lower coils in the same slot would not be commutated or reversed at the same moment.* This was

*U. S. Patent No. 588,279

accomplished by changing the throw of the coil from full pitch to one or more slots more or less than the full pitch. In two-circuit windings with one turn per coil, the end connector at one end necessarily has to span more than full pitch if the end connector at the other end spans less. This scheme of "fractional pitch," or "chorded" winding was soon tried out and proved to be quite beneficial, except in those cases where the neutral or commutating zone was too narrow. This arrangement was very widely adopted, and remained in general use until the commutating pole came in. With this, at first, full pitch windings were used, but now the "fractional pitch" or "chorded" armature winding has come into extended use in some types of commutating pole machines.

Equalizing Connections on Armature Windings

The various types of armature windings and their effects should be considered. As indicated before, the series or two-circuit winding was used principally on the early slotted armature machines of moderate capacity. The parallel drum type winding on multipolar machines was well known at this time, but most of the machines built were not large enough to require this winding. However, as larger capacities came in, it was recognized that the armature winding would have to be subdivided into more paths, principally on account of commutation, and the parallel type of winding began to be used. With this type of winding it was soon noticed that the commutating conditions were, not infrequently, considerably poorer than in the two-circuit winding, on the basis of equivalent windings and commutator bars. This was particularly true in machines with more than four poles. It was soon discovered that there was unequal division of current among the various parallel circuits, and tests indicated that this was due primarily to unequal e. m. f.'s generated in the different parallel circuits by inequality in field strengths of the different poles. This necessitated very careful adjustments of the air-gaps around the machine and, where the discrepancy was apparently due to the magnetic material itself, such as the poles or yoke, it was in some cases the practice to adjust the individual field coils to give the required equality of field magnetic strengths. This was a practicable but not very satisfactory situation. In some cases, the unbalancing was so bad that some of the parallel circuits would

feed back through others, so that the relative current unbalancing *was actually increased*. This action appeared to be as follows.—When any armature circuit carried a current, it tended to "cross magnetize" the field pole, strengthening the flux at one pole edge and weakening it at the other. Without saturation, these two actions should balance each other, so that the total pole strength remained practically constant regardless of the flux distortion. In consequence, the armature e. m. f. per pole should remain practically constant. However, with any considerable saturation in the path of the cross flux, the increased flux at one pole corner was not equal to the reduction at the other corner, so that the resultant total flux, and the e. m. f. were decreased. Assume, for instance, a ten-pole parallel-wound armature in a field in which one pole, or one magnetic circuit, was much weaker than the others. The stronger circuits tended to feed current back through the weaker. There would be distortion under all the poles, but if eight circuits fed current through two circuits, then the distortion in the two circuits would be much greater than in the eight. If there were high saturation in the path of the cross magnetic circuits, then all the magnetic fields would be weakened to a certain extent, but the two normally weaker ones would be weakened much more than the others, due to the larger currents. Thus their e. m. f.'s would be still further reduced and more current would flow through them. The action thus would become cumulative, and might increase until destructive local currents would flow in some of the circuits. In certain of the early parallel-wound machines, the writer observed some extreme cases of this action, in which the current gradually increased to such values that the carbon brushes became red hot over the whole length, and the sparking at the commutator was terrific. Measurements of the armature voltages in such cases, with the brushes raised, always showed considerable unbalancing.

The problem of unbalanced circuits in parallel-wound multipolar armatures was known and the conditions accepted for several years before a true remedy was found for it. As in many other cases, this remedy resulted from an unusually severe case of trouble. The Westinghouse Company had sold a number of high current machines for electrolytic work. These were built with 14-pole fields and parallel-wound armatures. The then usual methods of balancing the magnetic circuits were relied upon. However, on test, the first of these machines developed undue difficulty in maintain-

ing balanced magnetic circuits. The finest possible adjustments were necessary to obtain reasonably good operating conditions. Also, due possibly to the dimensions of the frame, and the lack of rigidity in the temporary foundation, the machine would get out of magnetic alignment very easily, and would get into vibration. As soon as vibration began, commutation troubles would commence and would grow worse. Mr. Philip Lange, then superintendent, gave this machine his personal attention with a view to finding how to adjust for permanently good results. After several days of adjustment, he became somewhat discouraged and told the writer that he did not believe that mechanical adjustment was a satisfactory solution of this difficulty. In discussing the matter, the writer suggested that, as two or more separate armatures, operating in parallel, would have their field strengths equalized by tying them together electrically through polyphase alternating-current connectors, therefore, as a parallel-wound multipolar armature was equivalent to a number of separate armatures feeding into a common direct-current circuit, it was theoretically possible to balance the different field fluxes by tying all the parallel armature circuits together by polyphase connections.* The writer at that time was very familiar with such action, through extended tests of alternators in parallel, rotary converters, etc.; also, having applied for a broad patent covering the principle of controlling the field strength of synchronous generators or motors by leading or lagging alternating currents.† After making this suggestion, as to a possible cure for the above trouble, he then proposed that it be tried on this machine in a comparatively simple manner by winding three insulated copper bands over the front end of the armature winding between the commutator necks and the armature core, and then carrying suitable insulated connectors from these bands to the tops of the commutator necks, using seven such connectors per ring. In this way, a crude but easily accessible set of polyphase connections was added to the machine. This work was carried far into the night before being ready to test. Mr. Lange left word that the results of the tests be telephoned him as soon as obtained. About midnight he received a message that the commutation was perfect and there was no vibration. He then suggested that, possibly, unusually good mechancial adjustment had been obtained in setting up the field, and that, therefore, the cross con-

*U. S. Patent No. 573,009. †U. S. Patent No. 582,131.

nections might not be responsible for the results. As a check on this, he asked that the cross connections be opened, without disturbing the machine otherwise in any manner, and the test then be repeated. Under this condition, the sparking and vibration were as bad as ever, or possibly worse than the average former results, for in setting up the field after adding the cross connections, no particular attempt had been made to obtain good adjustment of the magnetic circuit. The results therefore appeared to be conclusive, and the several machines on this order were then fitted with three-phase cross-connections, and all showed up equally well on shop test. A curious condition developed in one of these machines after installation in the customer's plant. It was found that one of the generators did not commutate as well as the others, and the reason for this was not discovered for several weeks It was then found that this machine did not have the same shunt field current as the others. Investigation then showed that two field coils had wrong polarity, namely, those marked No. 6 and No. 9. In assembling the field coils on the poles, the numerals painted on the coils had apparently been read upside down, and the coils thus interchanged. In those days, the field coils had the connections "open" or "crossed" inside the coil so that one could not determine from its outside appearance what its polarity would be. Here was a case where a 14-pole parallel-wound armature had operated for several months with *two field coils reversed*, and yet the armature cross-connections actually neutralized the wrong polarity and established fields of the correct polarity in their place. This was very good evidence as to the effectiveness of the cross-connections.

As soon as this method of balancing parallel circuits was developed, it was applied to all new machines being built by the Westinghouse Company, and was also applied to a large number of parallel-wound armatures already in operation. It was soon found that with three cross-connections, there was, in some cases, a tendency to "spot" the commutator at as many points or regions as there were cross-connecting taps to the commutator. These spots or regions were always between the cross-connecting taps to the commutator. To overcome this, four cross-connecting rings were tried on one flagrant case, and the spots were still found, but of less width than before. Six cross-connections were then tried on the same machine, with still evidence of a little spotting. A total of nine cross-connections was then tried and the spot-

ting entirely disappeared. This was then tried on various machines, with equally good results, and therefore a comparatively large number of cross-connections was adopted as standard Westinghouse practice. Sometime later, it was common practice to cross-connect all the commutator bars, but it was found that this apparently gave no better results than a considerably less number of cross-connections. Present experience seems to indicate that one cross-connection per armature slot is as far as it is necessary to go, even in the most extreme cases.

Cross-connection of parallel-wound armatures was gradually adopted by other companies, until now it is practically universal. Doubtless, most of the manufacturers have gone through the same course of development as indicated above, in regard to the number of cross-connections used. The first G. E. cross-connected armature that the writer saw had only two cross-connecting rings, but later, this was changed to 11 rings, the machine having 22 slots per pole. This was one of the things that everybody had to find out by actual experience. The use of cross-connections on parallel windings has undoubtedly had a very great influence on direct-current development, and yet normally it has appeared to be simply one of the incidental features of direct-current design.

In equalizing the e. m. f.'s by equalizing the pole fluxes, naturally the magnetic pulls around the machine should be equalized. This was recognized in the first place, but an actual proof of it was obtained very early in the practice. In one case, with a large engine-type machine, one of the engine pedestals slipped, the armature being thrown to one side until it was practically touching the field poles. With a non-equalized armature winding, the unbalanced magnetic pull under this condition would have been so great that the field would have "hugged" the armature presumably to the point of destruction. But in this case, the armature ran freely in the field, and there was no evidence of any magnetic pull or unbalancing, except possibly a slight sparking at the commutator.

In the early days, numerous attempts were made to retain the good features of the two-circuit winding, and still increase the number of armature circuits. This was mostly before the parallel winding had been perfected by the development of cross-connections. The most obvious method of extending the field of the two-circuit winding was by using two or more two-circuit windings on the same armature core and arranging them to operate normally

in parallel at the brushes. When the several two-circuit windings were entirely independent of each other, they were known as "sandwich windings." In other modifications of these windings, the various circuits closed on each other and formed the so-called "re-entrant" windings. The writer had some early experience with both these arrangements, but neither proved very satisfactory. In the first case tried, a direct-connected machine of moderate size had a sandwich winding, consisting of two entirely independent two-circuit windings connected to alternate commutator bars. This was run on test for 24 hours with excellent results. Fortunately, in order to do some special testing, it was then operated a few hours longer, and burning of alternate commutator bars developed. The burnt bars were marked, the commutator was turned down, and the tests were repeated. Burning again occurred. This operation was repeated several times with like results, except that it was noted that the same set of bars did not always burn. After possibly a week of testing, this winding was abandoned as impracticable. Apparently, similar results were found by other manufacturers, except that in some cases they got their machines on the market before they discovered the difficulty of burning alternate bars. Some years later, Prof. E. E. Arnold of Karlsruhe, Germany, developed a system of cross-connections for such armature windings which, to a great extent, overcame this burning action at the commutator. This system consists in interconnecting various points of equal potential in the different circuits. The writer at an earlier date similarly cross-connected some sandwich type two-circuit closed coil windings on some large multipolar low voltage alternators.* The arrangement of armature winding and cross-connections was the same as Prof. Arnold's patent of later date. If commutators had been connected to these alternator windings, the arrangement would have been the same as Prof Arnold's. These same machines are, the writer believes, in operating service at the present time.

Commutator Mica

While considering questions of commutation, the effect of windings on commutation, etc., the story of commutator mica should not be overlooked, for much interesting history is involved in this. The use of mica as an insulating material between commutator bars dates far back. In the latter '80's, the use of mica in

*U. S. Patent No. 680,793.

this way was well established, although red fiber and similar materials were still used occasionally. However, the mica practice in those days was not at all standardized or uniform. Various thicknesses of mica were used from possibly 1-32 up to 1/8 in. A thickness of 1-16 in. seemed to have the preference in the larger machines. With the surface armature windings, used entirely in those days, one thickness of mica appeared to serve as well as any other. Also, practically all mica was punched out of solid sheets and was unsplit as far as possible. In railway motors, 1-16 in. mica was also in fairly common use.

In designing the first slotted armature, single reduction railway motor in 1890, as already described, the mica between the commutator bars was made 1-32 in. thick, for some reason which the writer does not now recall. On test, the commutators of the first two machines, which were made with this thin mica, showed no mica trouble whatever. However, this *very thin* mica was noted in particular by the railway people, and a "howl went up" against it. In consequence of the great criticism, later motors were made with much thicker mica, although not nearly as thick as the general criticism called for. However, when these later motors went into commercial service, trouble soon developed at the commutators. Very bad blackening and burning of the commutator face occurred in all motors. It was soon noted that, in all cases of such burning, the commutator mica stood above the copper surface. It was not evident at first, however, whether the burning was inherent in the slotted type of machine, with the high mica merely as a result of such burning, or whether insufficiently rapid wear of the mica, compared with the copper, started the trouble. However, it was found that scraping down the mica, below the surface of the copper, stopped the burning action. It thus appeared that insufficiently rapid wear of the mica was back of this trouble. Undercutting of the mica was resorted to for awhile, but was considered as only a temporary remedy. In looking for a permanent remedy, the action of the first two motors built, with 1-32 in. mica, was carefully studied. It was noted that, although these two motors had been in service longer than any of the others, yet no tendency for burning or high mica had ever developed. This was a pretty fair indication of what to do, and therefore, a number of additional commutators were built with 1-32 in. mica, and installed in places where there was commutator blackening. All these new commutators were a great improvement, so that

many of the old commutators with thicker mica were changed to the 1-32 in. mica. This practically eliminated the trouble, but occasionally there were cases where black spots or regions developed on the commutators which could apparently be traced to local hard places in the mica. Thus the problem of more rapidly wearing mica came up, and various experiments were made to find such. The first effective step consisted in splitting the mica into a number of fine sheets before building it in the commutator, with the idea that its rate of wear would be increased in that way. This did prove fairly effective, particularly in large generators. As the slotted type of railway generator, however, followed about a year after the motor, fortunately the investigations of the motor troubles were then under way and their temporary remedies were applicable very early in the generator work. Sub-dividing the mica as described almost eliminated the motor mica troubles and did help the generators very considerably; but the generator trouble was harder to eliminate, because everyone was opposed to the use of 1-32 in. mica in generator commutators, and therefore a considerably thicker mica was retained. It was recognized that soft quick wearing mica was most desirable, and it was soon found that some kinds of mica were better than others. Thus the softer "amber" micas were soon chosen in preference to the harder "white" micas for use between commutator bars. Incidently, in connection with this question of soft mica, the writer recalls an incident which happened in 1892. A fire occurred in one of the Pittsburgh car barns which destroyed, among other equipment, a car containing two Westinghouse single-reduction motors. An examination of these motors was made by the writer after the fire, and it was found that the commutators had been apparently red hot. In dismantling one of these commutators, the mica between commutator bars which formerly had been in solid pieces, came out in the original form, but was semi-calcined to a white appearance, and was split into extremely thin laminae and appeared to be very soft. The writer suggested at the time that here was the kind of mica that we ought to have in commutators. However, it was considered of insufficient strength to use in commutators, the use of built-up mica with shellac or other binding material not being then well known.

The use of finely split mica without any binder, in commutators, lasted for a year to two. Such construction, however, required relatively large sheets of mica, which were unduly expensive. Then, "Micanite" which consisted of small thin laminae of

mica built up into sheets, with a suitable binder, came into use, and this eventually solved the mica problem, at least partially, as far as the material was concerned. But several grades of this built-up mica were developed, and various binding materials were used by different manufacturers, which eventually led to very serious trouble from "pitting," etc. In this pitting, sparks between adjacent commutator bars would gradually eat away the edges of the mica, and this action would follow the burnt edges until deep places were eaten down between the bars. All manufacturers of electrical machinery encountered more or less trouble from this pitting which, in many cases, was charged against the design of the machine. Eventually the cause was found to lie principally in the binding material in the mica plate, and with improvement in this point and care in keeping free oil off the commutators, pitting gradually disappeared.

Recognizing the fact that mica is not an unmixed blessing in commutators, various attempts have been made from time to time to find substitutes. Electrically, substitutes may be found without difficulty, but up to the present time, none of them have shown suitable physical properties, except in limited applications. "Red fiber" and paper were used many years ago on commutators of surface-wound machines, apparently with very good success. Such materials wore down rapidly under the brush, especially if any sparking occurred. Therefore, if high fiber should lift the brush away from the commutator face, the resultant sparking would soon burn the fiber down flush with the copper so that good contact between brush and copper would again result. This action in itself is an ideal one. However, all fibers or papers are subject to more or less expansion or contraction, due to moisture conditions, and this was a serious objection. If any considerable expansion of the fiber occurred in its thickness, that is, in the circumferential direction of the commutator, then, when shrinkage followed, due to drying out of the moisture, there would necessarily be some slight looseness circumferentially and oil or other foreign material could penetrate between commutator bars, which would eventually lead to pitting. What was required was a material with some elasticity, so that the space between commutator bars would always be filled solidly regardless of expansion or contraction of the commutator. The finely laminated structure of mica plate, furnishes the necessary elasticity, but apparently no other material yet available has satisfactorily met this condition. The phys-

ical conditions required however, were not as well understood many years ago, and hence the many attempts to use other materials than mica in commutators. The Westinghouse Company tried "fish paper" quite extensively years ago, in a number of low voltage machines. In the preliminary tests the material used appeared to be influenced but little by atmospheric conditions, and excellent results were obtained. However, in attempting to extend its use, very considerable difficulty was encountered in finding material which was as little affected by moisture as that used in the first tests. It developed that the particular qualities desired for this service were exceptional rather than normal, in the manufacture of this material. Thus it soon became evident that this material would not meet the requirements in general. Various other materials were tested, such as asbestos and paper built up in alternate layers, mica and paper built up in alternate layers, etc. While all of these were operative, yet, in general, they did not show sufficient promise to extend their use. Such experience and developments were not confined to the Westinghouse Company, for presumably all enterprising manufacturers have had more or less the same experience.

Within recent years, practice has tended very largely toward undercutting the mica. This has not been due to mica trouble primarily, but has arisen from brush conditions. Experience has shown that certain grades of brushes are electrically and mechanically very desirable, with the exception that they do not have sufficient grinding or wearing action on the mica. In order to obtain the full benefits of such brushes, in many cases, it is necessary to undercut the mica, and thus eliminate entirely the problem of mica wear. This is especially the case in those modern relatively high-speed machines with comparatively thin commutator bars, in which the thickness of mica represents a fairly large percentage of the bar thickness. In such machines, undercutting was first adopted, but as the beneficial effects of the better brushes became recognized undercutting has been very generally adopted on all high-speed machines, in order to use such brushes. This undercutting has been the latest important step in the mica problem.

Brushes and Brushholders

The types and constructions of brushes and brushholders have held a not unimportant place in the development of direct-current apparatus. On the very early apparatus, copper or metal alloy

brushes were used almost exclusively. These were even used on early railway motors, but the results could not be considered as highly satisfactory. It is hardly conceivable that electric traction could have reached its present high development if the metal brush had been retained. About 1887 and 1888, the carbon brush began to come into use and it is still with us, with no prospects of being displaced by anything else, except in very special applications, such as extremely low voltage work. It may be said that no one thing has had a greater influence on direct-current development than the carbon brush.

By the time the larger railway generators began to come into use, as described in the first part of this article, the carbon brush

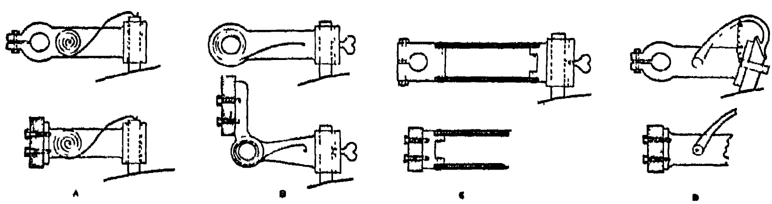


FIG 7—THE DEVELOPMENT OF THE BRUSHHOLDER
A—The sliding type B—The swivel type. C—Parallel motion type. D—Reaction type

was well established. However, the manufacture of such brushes in those days was rather crude compared with present practice, which also may be said of everything else in the electrical business. There was no wide range of varieties or grades to choose from, and the carbon was a carbon brush only. If there had been many grades, we probably would not have known how to apply them. We found what brush gave us good results in a certain case, and we stuck to it "through thick and thin." When there were troubles, they were frequently blamed on the mica or the brushholders. The latter were thus subject to continual change. Types came and went and then came back again. However, out of the multiplicity of brushholders, several comparatively distinct types arose, Fig. 7, such as the "sliding," the "reaction" (which was one form of the sliding type), the "swivel" and the "parallel-motion" types. Each had its good points as well as bad. All of these types are still in use to a certain extent, but certain of them predominate in present manufacture. It so happens that the one which is now furnished almost exclusively with the larger apparatus, namely, the sliding type, was also one of the earliest developed.

The early Weston type railway generator built by the U. S. Co. (described in the early part of this article), had a sliding type carbon brushholder. When the Westinghouse Company took up the manufacture of the multipolar generator, sliding carbon holders were used. As far as the writer knows, the early T-H generators also had sliding holders. The railway motors of that time, built by the Edison (Sprague system), the T-H, the Westinghouse, and the Short Companies, all had some form of sliding holder, and usually with the carbons standing radially to the commutator. In railway motors, there was a definite reason for this, for, as such motors operated in either direction, the radial carbon was assumed to give the best average working conditions. Also radial carbons were used on some of the early railway generators, but it was soon found that a slight inclination of the brushes to the face of the commutator allowed a somewhat smoother action, there being less chattering and less "screeching" in the case of highly polished commutators. It was a good deal like moving a pencil over a sheet of glass. With the pencil held too nearly vertical to the glass, there is liable to be chattering and screeching. Thus it soon became standard practice to incline the brushes when the sliding type was used.

In the early sliding type holders, it was found that when heavy currents per brush were carried, there was a tendency towards burning of both the brush and the inside of the brush box. In some forms of sliding holders it was attempted to overcome this by clamping each carbon tightly in a metal box, and arranging for the boxes to slide up and down on the holders. The transfer of current was thus between metal surfaces. But eventually this developed trouble. The obvious remedy for all these cases was to attach flexible shunts from the carbon itself to the solid frame of the brushholder. However, the designers had many trials and tribulations before this remedy was well developed. In the early Westinghouse generators, before the use of shunts became general, it was found that very long carbons were effective in preventing burning of the carbons in their boxes, and this practice was adhered to pretty faithfully for several years. Of course, the beneficial effects of the long carbon were largely in increasing the contact surface, and in lessening any tendency to chatter, as a long carbon would not "rattle about" in its box, as readily as a short one.

Due to the difficulty in transferring current from the carbon to the holder, in the sliding shunt type, the Westinghouse Company (and presumably all other companies, also)tried out various forms of the swivel type holder. In this type, the brush was clamped in a metal box which was attached to an arm which swiveled about a holder rod or pin. This soon showed trouble at the swivel contacts, due to the current, and therefore, shunts had to be attached from the swivel arms to the holder frame in order to protect the swivel joints or bearings. However, as this shunt connected metal to metal, it was not difficult to apply. This type of holder therefore, seemed to solve the problem. But another difficulty came up. About this time, engine-type generators came into general use, and it was soon found that the swivel type holder was liable to give trouble on engine-type machines, owing to the "weaving" action of the armature and commutator due to movement of the shaft in the bearings, resulting from the engine crank action. As long as the commutator ran perfectly true with respect to the brushholder, the brush faces would follow the commutator perfectly. But, with the brushholders hung from the generator field frame, or pedestals on the generator base, it may be seen that with any weaving action due to the engine cranks, the brush faces, with swivel holders could not possibly remain in intimate contact with the commutator face, and a periodic "heel-and-toe" contact would result. This necessarily meant sparking under the brush face, with consequent gradual burning away of the brush face and the commutator copper. Therefore, the commutators gradually "smutted"; that is, they got "dirty," and would show no polish. This, of course, was a fatal defect, and eventually put the swivel holder out of business, as far as the large engine-type generator was concerned. However, this type of holder had much greater success on self-contained machines, in which the commutator and brushholder could be made to run perfectly true with respect to each other.

Another type of holder which later came into use, and for which great claims were made, was the parallel-motion holder. This was somewhat similar to the swivel type, except that the brush box moved up and down parallel to itself through a parallel-motion arrangement. This parallel-motion part usually consisted of two parallel arms of flexible material, which were connected at one end to the brushholder frame and at the other to the brush box. The flexible arms were made of laminae of copper, bronze or

steel, and were flexible enough to allow a slight up or down motion, but were not flexible enough to make the holder unduly flimsy. In principle, this holder seemed a very good one, and it held its own for some years. The Crocker-Wheeler Company probably used this type to a greater extent than any other manufacturer. It appears to be applied but little at present, presumably due to questions of cost and space requirements.

A fourth form of brushholder, namely, the reaction type, is in reality, one form of the sliding type holder, for the brush slides up and down parallel to itself. In this holder the sliding brush is inclined to the commutator and holder at such an angle that the reacting forces tend to make it hug the brushholder face, and thus give contact between the carbon and holder. This type of holder was, at one time, applied quite extensively to railway generators by the Bullock and the Walker companies, and is still applied to small machines, to some extent.

During all these departures and variations in brushholder design, the straight sliding carbon type was still going through a course of development, which consisted principally in simplifying and "improving" the construction of the holder itself, and the application of shunts between the holders and carbons. This latter was no simple matter, and almost as much effort has been expended in suitably attaching shunts to carbon brushes as in developing carbon brushholders themselves. One great difficulty was that any new method of attaching the shunt to the carbon had to be tried out in actual service for a comparatively long period before it could be accepted or condemned, and usually it was condemned. A certain shunt attachment might prove perfectly satisfactory in one class of service, and would be almost worthless in another class. One principal difficulty was that the current, in passing from the carbon to the shunt, or vice versa, would tend gradually to eat away the points of contact so that eventually the shunts would loosen or lose contact. This was a pretty big problem, and in the early part of the development, the manufacturers of the electric machines usually attached the shunts, developing various methods of doing this. Later, however, the carbon manufacturers took up the matter and, in general, were able to produce simpler and better methods by attaching the shunt during the formation or manufacture of the carbon, the shunt thus forming an integral part of the carbon instead of being an after attachment. With the greater perfection of the shunt attachments, the sliding

type carbon holders began to dominate the field until, today, this type is most generally used.

There were, of course, many variations in the construction of the sliding holders themselves, such as in the types and arrangements of springs, the materials and methods used in the manufacture of the holders, the sizes and shapes of carbons, but these have apparently had no very controlling effect on the general development. In generators, the inclination of the carbon either toward or against the direction of rotation, was at one time a much mooted point, but apparently it has never been definitely decided which practice is better, as both are used at the present time, and apparently the choice depends upon local conditions, such as commutator speed, lubricating quality of the carbons, and a number of other conditions. In many cases, changing the holder from either direction of inclination to the opposite direction, has apparently helped the operation.

Grades of Brushes

In recent years, much more attention has been paid to the various grades of carbons, as regards their conducting and lubricating qualities, softness, etc. Graphite brushes, or the use of graphite in carbon brushes, was long ago recognized as furnishing some very good qualities. However, it was soon noted that brushes with much graphite in them were liable to give "smutty" or burnt commutators, at least in railway work. This was blamed largely on the brush, which was possibly true to some extent, but it was later recognized that the fault was partly in the inability of such lubricating brushes to wear the mica down rapidly enough. In some cases, two grades of brushes were used on a machine at the same time, part having high abrasive qualities and the others being of a graphite nature and furnishing good lubrication. With a better understanding of the problem has again come the use of graphite types of brushes, with undercut commutators, and they appear to be very successful in many cases. Thus a type of brush which, at one time, was condemned for railway work, has later come into extended use, due partly to changes in constructive conditions.

Where better conducting qualities in the brushes were desired, the so called carbon-gauze brushes have been used at times. These originated probably as early as 1892. They were used on large railway generators to some extent, but principally in connection with lower voltage machines. In these brushes,

sheets of fine wire gauze were embedded in the carbon during the manufacture.

The question of plated versus unplated brushes came up very early in the application of carbon brushes, and is not satisfactorily settled yet. One theory was that plating assisted in the transfer of current between the carbon and the brush box, reducing the burning action. Another theory was that there should be little or no flow of current between the carbon and box, and therefore, plating was harmful, especially on carbons with good shunts. Again, where the shunts have been attached simply to the outside surface of the carbon, it has been claimed that plating assisted in getting the current to the shunt. And the question is still open for discussion. In many cases probably it is merely a matter of personal opinion. There are so many variable conditions in each machine that one can get quite different results at different times, or under different conditions of service.

Burning of Brushes, "Picking Up Copper," Etc.

Ever since carbon brushes came into use there has been more or less trouble from burning of the brush faces, honeycombing of the carbon structure and picking up of copper. These do not always go together, but there are certain common causes for all these actions. In the very early slotted armature generators ample brush capacity was usually furnished. However, gradually the ratings of such machines were increased, without radical changes in the proportions, due largely to improvement in ventilation, so that eventually the carbon brushes were worked at very high apparent current densities (densities due to work current only). It was soon evident that the brushes were worked too hard, and steps were taken to improve this condition by increase in brush size, etc. Brushes were made thicker circumferentially, with a view to reducing the current density, the fact being overlooked, or not recognized, that the local or cross currents of the brush face were back of a considerable part of this brush trouble. In many cases these thicker brushes did not improve conditions, or were even harmful. This latter was proved to be the case, in many instances, by simply beveling the "toe" of the thick brush in order to reduce the breadth of contact. Very often, much better operation was obtained with these beveled brushes, although the apparent current density in the brush was increased, but in fact, the actual current density was decreased. This led up to an appreciation of the fact that the local current in the brush in many cases, was actually greater than

the useful or work current. The writer very early reached the conclusion that the apparent current density in carbon brushes was of no real importance in designs or guarantees, unless other conditions, such as thickness of brush, etc., were also apecified.

Due largely to too high actual current density in the brush, there was much trouble in some of the early machines from burning of the brush faces. This burning would begin at one edge of the brush and gradually travel across the whole brush face, until the entire face had been burned away and the brush tip badly honeycombed in some instances. This honeycombing was usually coincident with "glowing," that is, red hot spots would appear in the brush tips. Many attempts were made to cure such conditions by substitution of a different kind of brush, and sometimes with success, due principally to change in brush resistance, with consequnt change in local currents. But this was largely "cut-and-try". It was also found that improvement in the inherent commutating conditions would also lessen the brush trouble. Obviously, this simply reduced the local currents, which consequently helped both the commutator and the brushes.

Polarity

It was noted very early in direct-current work that the positive and negative carbon brushes did not act exactly alike. Those of one polarity would some times take a good polish at the brush face, while those of the other polarity would show but little polish. Also, the brush faces would sometimes have a coating of copper formed on them, or small particles of copper would embed themselves in the brush face. This action was not the same for both polarities. It was quite a long time before this unequal polishing and picking up of copper was even partially understood. Eventually it was found that when a current passed through a moving contact, such as that between a brush and a moving commutator, or collecting ring, there was a tendency for minute particles of the material of the contact faces to be eaten or burned away, depending upon the direction of current. When the current passed from the brush to the commutator, the brush face tended to eat away, while with current in the reverse direction, the commutator copper showed this effect. With low current densities in the points of contact, it was noted that this action was very slight. Also, the better the contact, that is, the lower the resistance of contact, the less this action was. In some cases the material burned away from one surface was deposited on the opposing face, possibly mechanically.

For instance, with a carbon brush and current passing from the carbon to the commutator, the commutator conditions were averaged, and it was only in the brushes that any difference would show. Long before this action was well appreciated it was indicated on the collector rings of certain rotating armature alternators and rotary converters. In some of these machines, with copper brushes on the rings, but with very high current densities at the brush contacts, it was found that the rings tended to wear out of round, with half as many low places as there were current alterations per revolution, or number of poles in the field. This was quite pronounced in some cases, but was usually blamed on loose brushes, because increasing the brush contact pressure usually helped it temporarily. The fact was, that this was a true burning action, as above described, and it was only in every other alternation that the current was in the direction which would burn the collector ring. The fact that the different collector rings did not have their low spot in phase with each other was not appreciated for a long time.

With the carbon brushes, this action between the commutator and brushes became much more pronounced as the apparent current densities were increased. Also, picking up of copper became more pronounced. Both brush polarities suffered a great deal from burning. One polarity would have the brush face burned away due to the direction of current, this action being cumulative for, as the face burned away at one edge, due to the sum of the local and work currents, the contact arc would be decreased, and the contact would continue to burn away, although the local currents would be lessened. On the other polarity, where such burning should not be expected, a coating of copper would form in some cases, and this would tend to lower the brush contact resistance, and thus increase the local currents, which depended upon the contact resistance. Thus the brushes of this polarity would also be burned, due to the excessive current. Moreover, as the copper deposit was frequently very irregular, the reduction in brush contact resistance would be local only. At the spots of lower resistance, an excess part of the work current would flow, tending to produce local heating. As the temperature coefficient of resistance of carbon is negative, any local heating would mean still lower local resistance, a larger percentage of the total current concentrated at this point, and thus more heating, the action becoming cumulative, until glowing occurred at times. This abnormal local heating tended to

disintegrate the brush, so that cavities formed at or near the brush tip and the carbon became "honeycombed." This action was not always coincident with "picking-up-copper," for anything which produced unequal division of current among the brushes or over the brush contact, tended toward glowing and honeycombing. This action apparently was more closely connected with high current densities, either locally or as a whole, than with any other cause. Obviously, with the brushes worked normally very close to the limit as regards permissible current densities, any little inequalities in current were liable to have a more pronounced effect.

This action has been dealt with rather fully, as it was one of the very serious troubles in old time machines. Many attempts were made to overcome this trouble by changing the kind of brush, the type of brushholder, proportions of the armature, etc., and with varying success. Burning of the brushes was frequently accompanied by high mica on the commutator, and this in turn exaggerated the burning. Undercutting the mica, by allowing more intimate contact between the brushes and copper, quite frequently alleviated this condition. But where the actual current densities were very high, even undercutting did not cure the trouble. Eventually, it was recognized that lower actual current densities must be had, and when this was thoroughly appreciated and embodied in the designs, burning of brushes and picking up of copper were of much less usual occurrence. In the commutating-pole machine, referred to later, the local currents are under partial control, and thus the apparent current densities in the brush can be brought up much nearer to the actual limiting densities, so that today considerably higher apparent densities are used regularly.

The above covers one principal cause of brush trouble. However, there were many cases of trouble in which the brush densities were not unduly high, considering the size of brush face, but where the effective brush contact area was reduced by bad mechanical conditions, such as chattering of the brushes, commutators out of round, etc. It was not always possible to distinguish between the various causes of brush burning and, not infrequently, a remedy which worked in one case was an entire failure in the next. Unequal division of current between different brush arms in parallel, and also between the different brushes on the same arm, also greatly complicated the problem. Back of this is the negative temperature coefficient of resistance of the carbon brush, as mentioned before. With a positive coefficient, any local increase

in current would be opposed by a local increase in resistance, thus tending to equalize the current distribution between the various brushes. However, with the negative coefficient, a more or less unstable condition exists. This unfortunate condition has been recognized for many years and presumably it has been a serious handicap in direct-current design and development Various devices for overcoming it have been suggested from time to time, but no very practical one has yet been produced.

Brushholder Supports

Having dealt with brushes and brushholders, the brushholder arms and supports should be given consideration, as there is some interesting history connected with this feature of design. In the earlier machines the brushholder arms or supports were carried by brackets attached to or surrounding the bearing. This was common practice in all early belted machines. Provision was usually made for some easy, quick method for rocking the brushes forward or backward to suit the commutation. Even on the railway generators, where the point of commutation was supposed to be fixed, such brush-rocking devices were always furnished, so that the best average position of commutation could readily be found.

When the engine-type generator came in, new problems were encountered. In the first place the engine bearing was not always a suitable place to attach a brushholder, and in the second place, with large diameter commutators, this made a rather flimsy support for a large diameter of holder. Also, a new problem came up in the weaving action of the armature of the engine-type generator, as already referred to. If the brushholder frame was held stationary, then the weaving action of the commutator meant continual motion of the brushes up and down in their holders, which was considered undesirable. In one early Westinghouse engine-type generator, an attempt was made to make the brushholder follow the commutator by suspending it directly on the engine shaft by a sleeve or bushing which fitted over the shaft, thus forming a bearing. This was prevented from rotating with the shaft by means of a brace to some stationary part of the engine frame. This worked for awhile, until one day the bearing "froze" on the shaft, the brace broke, and the brushholder started to rotate around the commutator. This ended the history of that particular type of support.

The next step in the development of the brushholder support consisted in hanging it from the field yoke, either centering it in

the yoke itself (early Westinghouse practice) or centering it on a number of rigid arms extending out from the yoke toward or over the commutator, (early G. E. practice). Of course, these two methods were practically equivalent. Eventually, for purely constructive reasons apparently, centering in the yoke itself became the general practice and is standard practice at the present time in the larger machines. This method of support did not eliminate the difficulty from weaving action of the commutator, but in furnishing a rigid brush support, the resultant troubles, due to weaving action, were partly overcome and the development of good sliding type brushholders took care of the rest.

Another trouble developed occasionally, principally in connection with brushholders for long commutators, that is, wide commutator faces. The individual brushholder arms would sometimes vibrate or chatter badly. At first, it was attempted to make the individual arms rigid enough to take care of this, but as each arm had to be insulated from the brushholder frame, it was difficult to obtain sufficient rigidity without undue complication and expense. As an alternative, the practice was adopted of tying adjacent arms to each other at their ends by means of insulated supports, so that the entire system of brush arms thus formed one rigid body. This was very effective and is standard practice today.

On the earlier machines, the brush arms, to which the brushholders were attached, were made of brass or some other fairly good conducting material. For some reason or other, iron was considered objectionable, and it was many years before it came into general use for the brushholder arms. Now it is standard practice. Possibly, commercial reasons may have influenced this delay in the use of iron in brush arms, for it was criticised as being "cheap" in appearance.

Commutators

Commutators and commutator constructions also have a history, but it is rather difficult to trace this systematically. Very early in direct-current generator practice, the present "V" construction for supporting the commutator bars was developed and, with various minor modifications, it has come through to the present. This construction, Fig. 8-*a*, was adopted on the earliest Westinghouse multipolar generators and, with only one exception, namely, the shrink-ring construction in turbo-generator commutators, it has been retained on these machines throughout. The

angle of the V's, the shape and construction and material of the insulation have varied from time to time, but this general method of supporting the bars has remained unchanged.

Another early method of supporting the commutator bars, which was used considerably by some manufacturers, including the Thomson-Houston, if the writer remembers rightly, was as shown in Fig. 8-*b*. This was apparently a fairly satisfactory construction in the early days, but was abandoned later by practically everybody, in favor of the V construction. When built-up mica insulating bushing came into use for insulating the commutator

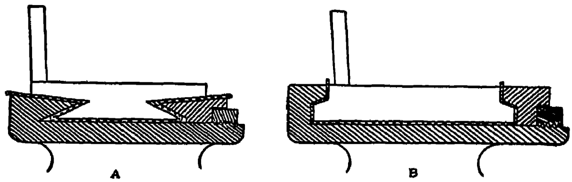
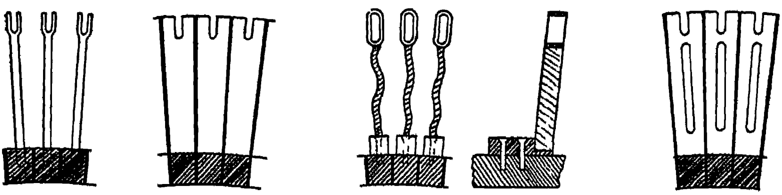


FIG. 8—TYPES OF COMMUTATOR BAR CONSTRUCTION

bars from their supports, apparently the V-ring construction was simpler as regards mica bushings than any other construction, and this may have been enough to turn the manufacture toward this one construction.

In the early days, there was a great variety of methods of attaching the armature windings to the commutator. In some cases, the commutator was made without "necks" in the modern sense of the word, the windings being carried directly to the commutator face and attached thereto by solder or screws. When railway generators began to come in, the Westinghouse Company used comparatively long necks to which the armature conductors were attached by means of slots in the end of the necks in which the conductors were laid and then soldered. In some cases, these necks fitted tightly against each other with mica between, as between commutator bars, as in Fig. 9-*b*. In other cases, especially where the commutator bars were comparatively wide, thin separate necks with air spaces between them were used, Fig. 9-*a*. Usually these necks were made of copper strap, riveted or soldered to the end of the bars. In other cases, the neck and bar was sawed out of one piece. The open neck was most common in the larger Westinghouse generators. In practically all cases, these necks were made so stiff that they were self-supporting and required no insulation between them.

In the Thomson-Houston and early General Electric large railway generators, these necks were frequently made of flexible material, and were usually insulated throughout their length in consequence. With the built-up type of strap winding used on these early machines, as has already been described, presumably these flexible commutator necks were of material advantage in winding and connecting. In many cases, these necks were attached to small brass or copper blocks or terminals, of rectangular shape which, in turn, were attached to the commutator bars by means of screws so that they could be disconnected, if desired, Fig. 9-*c* and *d*. Eventually the rigid neck construction came into general use.



A B C D E

FIG. 9—METHODS OF CONNECTING COMMUTATOR BARS TO ARMATURE WINDINGS

Material

There was quite a variety of materials tried out in the earlier commutators. For the bars, copper, either drawn or rolled, has been used from almost the earliest times, but many attempts have been made to get away from this material, largely on account of the expense. Various brasses and bronzes, and even cast copper, have been used quite extensively, and not entirely on account of lower cost, for some of these were about as expensive as drawn copper. One idea was that the rapid "wear" of copper commutators which was sometimes encountered, was due to the softness of the material and that, therefore, some much harder kind of material would give less wear. Of course, it was not known then that the rapid wear in those cases was not true frictional wear, but was due to burning under the brushes, to high and hard mica, etc. This wear was a principal reason for using the various brasses and bronzes. After long trials of each of these materials, the conclusion was usually reached that the average results were no better than with copper. In some of the early Westinghouse experience, cast segments were used, with apparently good results. However, in the larger bars, blow-holes were liable to be found near the

center of the bar. This was taken up with the manufacturer of these bars, but the trouble was not entirely overcome.

One rather amusing case of trouble came within the writer's experience in connection with one of these early cast copper commutators. This was a fairly large capacity, low voltage belted machine, with very thick commutator bars. The commutator ran very hot in the early service, due largely to brushholder troubles, and the writer was surprised to find solder was being thrown over everything in the neighborhood. He looked the commutator necks over, but could not find that any solder was missing at these points. Throwing of solder still continued, and in comparatively large quantities. Then the man who had charge of the building of the commutator was questioned, and he asked, innocently enough, whether this could have resulted from filling blow-holes in the commutator bars with solder. He then explained that the heavy cast bars had developed so many and such large blow-holes some distance below the wearing surface that he had thought it best to fill them up with solder. It may be added that eventually, this commutator ran all right, either due to lower temperature or to the escape of all the solder that could find an outlet.

As the mica and brushholder troubles were gradually eliminated, it became much better recognized that pure copper rolled, drawn or hammered—was about the best possible material for commutator purposes. It took time and additional experience to prove that this was the best polishing material. Various tests were made with iron, aluminum and other materials, in comparison with copper, and it was found that copper polished best of all practicable materials, under heavy load conditions. It was found that other materials under sparking conditions developed minute globules or "beads" on the commutator face, and these beads were liable to be very hard in some cases, so that they destroyed the brush polish, and also prevented the commutator face from polishing. The conclusion drawn eventually was that the copper was so much better a conductor of heat that these tiny metal beads would not be formed, as the heat would be conducted away too rapidly. Iron was particularly bad in this regard. Since the good characteristics of copper have been more thoroughly recognized, this material has been used almost exclusively.

With the exception of the bars, about the only materials which need be considered are the insulation and the supporting rings. In the early days, the supporting insulation, under the

metal clamps, was made of almost any kind of sheet-insulating material, such as paper, fiber, oiled canvas, or sheet mica. When built-up and moulded mica came into use, this was quickly adapted to commutator purposes, and is still standard practice.

One of the most serious problems in commutator insulation, in general, has been that of keeping out oil. Where oil could creep into the commutator, it was very liable to carry copper and carbon dust with it, and incipient short circuits or arcs sometimes resulted which developed into more serious trouble. One of the great problems has been to obtain "tight" commutators. Modern practice seems to be pretty successful in this. In the question of tight commutators, there have long been two schools, (or two sets of advocates), one favoring the so-called "arch-bound" construction and the other the "drum-bound." These terms practically define themselves. In the arch-bound construction the commutator is drawn down until the circumferential pressure is the limiting resistance. In the drum-bound, the commutator is drawn down until it binds upon a central drum or support which is the commutator bush. One advantage claimed for the drum-bound construction is that the commutator is affected less by temperature, as the circumferential pressure is not a controlling condition. Moreover, it is claimed that it is easier to assemble such a commutator. Against this, the claim for arch-bound is that it gives greater tightness than the drum-bound, and tightness is a most essential characteristic in commutators. For many years the writer has favored *tight* commutators, as his experience with pitting, (dealt with under the subject of mica) indicates that tightness is a necessary condition. At the present time, the so-called V-bound construction which might be considered as intermediate between the arch and drum-bound constructions, seems to be the most satisfactory, in general.

It is not necessary to say much about the supporting rings for commutators. On the early machines, these were frequently made of cast iron. When engine-type machines came in, the supporting rings were usually made segmental as they had to be split to get them over the shaft, the low commutator speeds allowing segmental construction without danger. However, as higher speed machines began to come in, such as rotary converters and motor-generators, solid supporting rings of cast steel or wrought iron came into very general use. This was not due altogether to the higher speeds, but was partly due to the necessities for making tighter commutators

than formerly, which necessitated stronger materials in the supporting rings.

Wearing Depth of Commutators

Practice has changed greatly in this feature, especially in recent years, due partly to improvements in design, and partly to a recognition of consistency in proportions. On very early generators and motors, the wearing depth of commutators was, rightly, very large. As commutators "wore" rapidly, due to high mica, poor commutation, etc., they had to be sandpapered or turned down rather frequently. A good part of the commutator was thus wasted. But when engine-type generators came, with their much better commutating characteristics, the great wearing depth was retained in general, apparently largely for traditional reasons. Some of these engine-type generators did not require even sandpapering once in two years, and yet any proposed reduction in wearing depth was looked at askance.

To illustrate the above, the following incident is cited:—The writer broached the subject of commutator wear with the engineer of a large railway system, in which 2½ in. wearing depth of commutators was standard practice with his larger commutators. He was asked how much the large commutators had worn down in the previous nine years, of pretty steady operation. The answer was, "About one-sixty-fourth of an inch." "Then, at that rate, how long will your commutator last?" After a little figuring, —"About 1500 years." "And how long will the rest of the machine last?" After a little thought,—"Not over 50 years at most." By actual figures, a 3-32 in. wearing depth in this case, corresponding to 50 year's life, would have been an absurdity of the opposite extreme. But a factor of safety of ten would have given a total available wearing depth of one inch, while the commutators actually had 2½ times this. The extra material is thus useless during the actual life of these machines. As the inconsistency of abnormal wearing depths, usually specified for commutators, became better realized, they were gradually decreased. This, of course, had to be recognized by the users of such apparatus, as well as the manufacturers. With the advent of the commutating-pole machines, with their better commutating characteristics, the wearing depth of commutators has been reduced to a fairly reasonable amount, still allowing a wide factor of safety. It is somewhat saddening to think of the thousands of tons of copper tied up uselessly in abnormal commutator proportions, but then

one has only to look in various other directions to see what possibly may be similar extravagances some of which are in full force at the present day, especially in methods of rating and applying electrical apparatus.

Temperature and Ventilation

One important general subject has not yet been touched upon very fully, namely, that of temperature, together with the related subject of ventilation. In the early days, all electric machinery ran hot and the manufacturers, as a rule, knew why the apparatus ran hot, but did not know just how to remedy the case. Armature cores were ventilated to a limited extent, but the windings were very poorly ventilated. The temperature of the windings was high (how high nobody knew or appreciated) but as no one had any particular experience with lower temperatures, the high temperatures were taken as a matter of course. This was particularly true of some of the early railway generators. On continuous full-load run, some of these would reach 125 degrees C. by thermometer, but as railway load in those days was far from continuous, this apparently did not make any difference. A rise of 60 to 75 degrees C. was considered fairly good on continuous temperature test. However, it was decided about 1892 that some lower standard, such as 40 degrees rise, should be adopted. When this went into effect in the Westinghouse testing room, some very amusing incidents occurred. The testing room men who had been accustomed to rises of 60 or 70 degrees would be much worried over nominal 40 degree machines which actually showed 42 to 45 degrees rise, as they feared the machines might burn up on test. They seemed to accept the newly set 40 degree limit as an absolute limit of safety, regardless of past experience.

After the 40 degree limit was adopted, it has stayed with us more or less constantly until the present time. The writer does not know where this exact limit originated, nor who was back of it. It just came and stayed.

In those early days temperature measurements could be made by thermometer about as accurately as at the present time, but people did not know how to hunt for hot spots and, in consequence, were liable to put the thermometer on the coldest part of the winding, and then wonder why such a cool machine (60 to 70 degrees C. rise) should burn out so readily. But what they did measure, they aimed to measure carefully.

In those days all temperatures were measured after shut down of test, and usually by covering the thermometer bulb with a great wad of cotton waste. But the thermometers used were not particularly accurate, and variations of five degrees or more between different thermometers tested at the same air temperature were found by the writer in a number of cases.

In this early work, some almost unbelievable incidents occurred. For instance, one of the routine testing men one day announced to the writer that he had found a method of cutting the temperatures of railway motors (old double reduction surface-wound armatures) to about one-half. He claimed he had accomplished this repeatedly and was sure of his results. As this appeared to be a very valuable idea, he was urged to divulge his method. After a good deal of coaxing, he stated that he had attained this result by leaving the waste off the thermometer while taking the temperatures. This was a case of absolute faith in what the thermometer said. A little explanation of the functions of the covering pad of waste, and of the principles of temperature measurement, soon put this man in the right.

As soon as the necessity for lower temperatures was recognized, the problem of ventilation became very active. Armature windings were arranged for more or less effective air circulation, and special ventilating ducts were placed in the armature cores at intervals. The writer does not know who first introduced ventilating ducts in the armature cores, but they did not originate in the Westinghouse Company. With the surface-wound armatures of course, there was little or no occasion for radial ventilating ducts, as the armature surface was pretty thoroughly covered up. Openings or holes parallel to the shaft were, however, rather common in surface-wound armatures for alternators, but in direct-current machines, except of the ring type, even such ventilation was usually impracticable. However, with the advent of the multipolar railway generators, with the drum armature windings and slotted armature cores, there was an opportunity to use radial ventilating ducts effectively, and they soon came into general use. The Thomson-Houston Company preceded the Westinghouse Company in the use of such ducts, according to the writer's memory. However, by the time that engine-type railway generators had practically monopolized the field, radial ventilating ducts in armature cores were standard practice with practically everybody, and this is standard construction at the present

time. Many varieties and constructions of ventilating ducts have been devised and tried out. About the only important departure from this construction has been in armatures equipped with ventilating fans at one end in which the air is drawn axially through the armature instead of radially. This has been used mostly on recent railway motors, and on certain lines of industrial motors.

The ventilation of direct-current armature windings has varied much, depending upon other controlling conditions. For instance, the end windings of railway motors were formerly much better ventilated than at present, and with very beneficial results as regards temperature. However, the railway motor, being an enclosed machine, circulated its own dirt (carbon and copper dust,) to such an extent that the windings, especially back of the commutator, would become so coated that surface leakage became serious. To overcome this, practice gradually tended toward unventilated end windings, that is, they were so completely boxed in that the dust trouble was pretty thoroughly eliminated. But the railway motor may be considered as an exceptional case, due to its normal inaccessibility for cleaning, and the tendency in other classes of machines has been toward *better* ventilation, rather than the reverse.

In commutators, the subjects of temperature and ventilation have always been with us, and probably are destined to stay with us as long as the business lasts. Primarily, the reason for this is that the commutator, in large machines, is so costly and sometimes so difficult to construct, that the natural tendency is toward crowding it down in dimensions, with a resulting tendency to increase the temperature. Thus the battle between size and temperature is always on.

In the very early railway commutators, in belted type machines, the temperature of the commutator, like all the rest of the machine, was usually fairly high. However, these early commutators were not very large, so that expansion troubles were not very serious. After the multipolar generators came in, it was soon found that long commutator necks, with air spaces between them, Fig. 9-*a*, were quite effective in cooling the commutator. The writer had this impressed upon him particularly in connection with an early direct-connected railway generator in which the necks and mica were solid clear up to the outer periphery where the winding joined the commutator, Fig. 9-*c*. The speed of the armature was

only 140 r. p.m., and the diameter of the commutator was small, so that the ventilation was comparatively poor. This commutator ran very hot on test. It was concluded that the solid necks had much to do with this, as these did not permit the usual heat dissipation which probably occurred with open necks The writer then had long radial slots milled in the center of the bars, as shown in Fig. 9-*a*. This set up a slight air draft across the commutator. The reduction in temperature was so pronounced that the writer became a thorough convert to the use of ventilated necks, and he adhered to such construction as far as possible on all large commutators thereafter. However, when engine-type generators came in, the commutators were usually made so large, compared with belted machines, that the temperature problem practically disappeared as far as commutators were concerned. However, when rotary converters and motor-generators became the prevailing practice, with the general introduction of the polyphase system in railway and central station work, this problem of temperature again became active, and has become more important as the speeds and ouputs have increased, so that today the problem is a "real live" one. In modern commutators, auxiliary "necks" or ventilating vanes are sometimes attached to the outer ends of the commutator bars, or ends farthest from the winding. Like the open commutator necks, these are quite effective in dissipating the commutator heat.

Various rules have been developed from time to time for determining the size of commutator required for a given current, without overheating. However, all such rules have proved to be only crudely approximate, for the heating is dependent upon the commutation and friction losses, which are extremely variable in different types and sizes of apparatus. The modern commutating-pole construction of machine, which furnishes a means for partially controlling the commutation losses, has been a great help in the commutator heating problem. This however, has simply allowed higher speeds with correspondingly smaller diameters of commutator for a given output, and thus the battle between size and temperature goes on.

In the modern high-speed motor-generators, probably the ventilation has been carried farther than in any other class of direct-current apparatus. In the modern machine, two fundamental conditions in the problem of ventilation are recognized, namely: supplying a sufficient quantity of air to carry away the

heat, and so distributing this air that it can take up the heat with the least temperature drop in the various parts of the machine. The whole modern theory of ventilation is built up upon these two conditions.

Special Classes of Direct-Current Machines

In the foregoing, direct-current generators and motors in general have been considered. However, there are several rather special classes or types of machines which merit separate consideration, in some of their features. Among these are double-commutator machines, turbo-generators, unipolar generators, and double-current generators (a.c.-d.c. machines). Also, commutating-pole machines in general have not been taken up, but as these represent practically the latest great step in the direct-current development, and therefore are newer in history than the above special types, the latter will be considered first.

Double-Commutator Machines

By this is meant an armature with two separate commutators, usually placed at opposite ends of the armature core. Such machines usually have been designed only for very special purposes, such as the collection of very heavy currents, or where two separate voltages are desired from the same armature core. Obviously, where the current to be handled is too large to come within the limits of a single commutator, the first suggestion would be to add a like commutator on the other end of the armature, and preferably connected to the same armature winding. This looks like a simple, easy solution of the problem, and so it proved to be from the mechanical or constructional standpoint purely. From the electrical standpoint, it sometimes proved to be a very unsatisfactory construction.

The earliest machine of this type that the writer had any practical experience with was built by the United States Company about 1890, this being of the Weston type, previously described. This was a two-pole, 200 kw, 60 volt machine and had a commutator at each end connected to a common winding of the surface-wound type. This machine was not very successful and was later provided with a slotted type of armature, which was also not entirely successful, due largely to the fact that copper brushes were required to handle the large current.

In 1893, the Westinghouse Company built some 60 volt, 3600 ampere, six-pole belted generators with two commutators connected to the same winding. These had carbon brushes. No particular trouble was encountered in the operation of these machines, except it was found that rather careful adjustment of the two sets of brushholders was necessary in order to produce proper division of load. After this, from time to time, double commutator machines of moderate size were built, and it was found in some cases that it was difficult to divide the load equally between the leads from the two commutators, and at the same time obtain good commutation at both sets of brushes. Various schemes were introduced for overcoming this trouble. In some cases, the leads from the two commutators were tied solidly together, and the ammeter was connected in the combined circuit. The brushes on the two commutators were then shifted until best commutation conditions were obtained. Later experience showed pretty clearly that, under this condition of best commutation, the two commutators were usually supplying quite unequal currents, especially where both were connected to one armature winding. This cured the trouble simply by hiding it. In one plant, where some 4 000 ampere, 250 volt; double commutator generators were installed, it was found that with the best commutation, one commutator supplied 3 000 amperes, while the other furnished only 1 000. No adjustment of the brush lead would overcome this and maintain good commutation. When one commutator carried 3000 amperes without sparking, then the brushes on the other one could not be rocked from the 1 000 ampere non-sparking position into a position where it would divide current equally with the other commutator, without sparking. There appeared to be no non-sparking position which would give equal current division. Finally, a low resistance in the form of a heavy cast iron grid, was introduced into the leads from the higher current commutator, with the brushes on both commutators set for the best commutation. This forced a larger percentage of the current to pass through the other commutator, and thus equalization was obtained. It was surprising how little was required to balance the two commutator loads. This case illustrates the general difficulty which appeared in double commutator machines of larger capacity when one winding only was used. This led the Westinghouse Company to advocate two independent armature windings when double commutators were required. With this arrangement, any equality of current would mean in-

equality in resistance drops, which would tend to equalize the loads A number of armatures of this type were actually built.

It may be of interest to note that the largest capacity, highest speed machine ever built by the Westinghouse Company had two commutators connected to a single armature winding. This was the generator end of a flywheel type motor-generator set for furnishing current to a reversing mill at the Illinois Steel Company's plant in South Chicago, and was rated as a 3 000 kw, 375 r. p. m , 600 volt machine. In this case, however, the commutators feed into separate loads, which are adjusted to divide approximately equally. The armature of this machine has some unusual constructive features. On account of the large output and high speed, and the fact that the load varies with great rapidity, it was desired to obtain the effect of one-half-turn armature coils instead of the one-turn coils, which are usual practice. The armature winding was made of the usual parallel-drum type with one turn per coil, but with only half as many coils as there are bars in each commutator. The commutators were connected to the winding at each side of the core in the usual manner, except that only alternate commutator bars were connected. Then, from the active bars on one commutator, strap connections or conductors were carried under the armature core to the idle or intermediate bars of the other commutator, and from the active bars of this second commutator similar conductors were carried through to the intermediate bars of the first commutator. Thus the potential of any intermediate commutator bar was midway between the potentials of the two adjacent active bars, and the result was equivalent to the use of a half-turn winding on the armature. As far as the writer knows, this is the only large machine ever built with this type of winding. It has been in successful operation for a number of years.

Another type of very large capacity, high-speed double commutator generator was built by the G. E. Company for the Niagara Falls plant of the Aluminum Company of America. These machines are of 3 500 kw capacity, 600 to 700 volts, 300 r. p. m. and are direct-coupled to waterwheels. Each commutator carries brushes of one polarity only. The number of poles in each machine is comparatively large and, in consequence of this and the high speed, the distance between commutator neutral points is relatively small, and, presumably to avoid crowding the brushholders too much, alternate holders are omitted. Thus one com-

mutator has only positive brushes, and the other only negative. This increased the distance between brushholders, but, of course, did not increase the distance between adjacent neutral points on the commutator. Therefore, as regards flashing around the commutator, this double spacing of the holders may be considered as more or less fallacious. Due to this arrangement of brush holders, some unusual commutator and brushholder operating conditions were found The two commutators of each machine did not polish, or "wear," equally, due largely to the fact that in one commutator the current flow was entirely from the brushes to the commutator, while in the other it was the reverse, the effect of which has already been described under brushes and commutation. However, these machines have been in operation for a number of years, and the above is not intended as a criticism of this particular design, but is merely to call attention to a very unusual construction.

The Bullock Company, some years ago, built some large capacity double-commutator machines for the Massena plant of the Aluminum Company of America. In these machines, unbalancing of the commutator current was encountered. This condition was corrected by the use of brushes of different resistance in the two polarities of each commutator.

It should be evident from the preceding that the double-commutator machines, in large capacities, as built by various manufacturers, have necessitated either special operative, or special balancing conditions. The trouble is, to a certain extent, an inherent one. The advent of the commutating pole apparently has not improved the position of the double-commutator machine, and at the present time such machines are only recommended where some very special conditions require such construction.

Direct-Current Turbo-Generators

Direct-current generators, driven by steam turbines, were introduced in this country many years ago by the DeLaval Company. However, these generators were geared to the steam turbines and operated at only comparatively high speeds. They were not turbo-generators in the modern meaning of generators direct-coupled to the turbine. It is in this latter type that special features are involved.

Probably the first true turbo-generator which was tried in commercial service in this country was one designed by the Westinghouse Company in 1896 for direct connection to a Parsons

5 000 r. p. m. turbine. This generator was designed for a capacity of 120 kw at 160 volts. When one considers that this machine had a speed of practically double that of the modern turbo-generator of corresponding capacity, it may be appreciated that this was quite a problem for a first machine. This was one of Mr. N. W. Storer's early "pets," and it required an extraordinary amount of petting to make it behave.

The real operating difficulties in this machine were due to the exceedingly high speed. There was no undue difficulty in making an armature which would hold together. The armature had partially closed slots with two rectangular straps shoved through from one end and then carefully formed at each end, over supporting shelves or brushes. There was a commutator at each end. The commutator peripheral speed was over 8 000 feet per minute, and herein occurred the real troubles with the machine. There

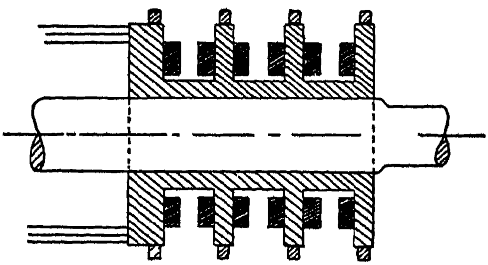


FIG. 10—RADIAL TYPE COMMUTATOR

were four poles and four brush arms, with carbon brushes originally, and graphite brushes later. Neither carbon nor graphite was successful, as intimate contact between the brushes and commutator apparently could not be maintained at the high commutator speed. Fine V-shaped grooves were then turned in the commutators, and brushes of parallel brass wires were used, similar to those on some machines in England. These brushes maintained pretty fair contact, but with the slotted type armatures used, the commutating conditions were not satisfactory enough to allow the use of metal brushes. There was always more or less sparking at the brushes, so that, after a certain amount of service, this machine was taken out. It was redesigned later for a speed of 3 600 r. p. m., but apparently was never completed.

Turbo-generator work was then dropped by the Westinghouse Company, until 1904, except that, for several years previous

to this, exciters had been built from time to time for direct-connection to turbo-alternators at both 1 800 and 3 600 r. p. m. These, however, were usually standard machines of small capacity, simply modified for these high speeds. Previous to 1904 the G. E. Company built and put in service a number of turbo-generators of moderate size, which operated with such success as to encourage the growth of this business. In 1904 the Westinghouse Company again took up this work, and three units were designed of 100 kw, 200 kw and 500 kw capacity, the latter for 600 volts for railway work.

The 100 kw unit was designed for a speed of about 2 000 r.p.m. and did not prove such a difficult machine to build or operate. The 200 kw was designed for 250 volts. Two of these machines were put in operation and eventually developed commutator trouble. New commutators were then furnished of the radial type, such as the British Westinghouse Company had been building. In this radial type commutator, as shown in Fig. 10, the brushes were located in grooves in the commutator and bore on opposite faces of the grooves. By this construction, much higher commutator speeds were allowable, as radial vibration, or radial inequalities of the commutator did not affect the brush contact. The only two machines of this type which were built are still in service. The radial commutator construction, however, as used on these two machines, proved unduly expensive, and no more were built for service.

The 500 kw, 600 volt turbo-generators operated at a speed of 1 500 r. p m. The commutator speed was about 5 500 feet per minute. The shrink-ring type of commutator construction was used. As the metal of these rings was very close to the commutator face, any little arcing or sparking was liable to bridge over to the rings and thus cause the machines to flash over. It was therefore necessary to insulate these rings completely in order to prevent flashing. This, however, was successfully accomplished. In service, these Westinghouse machines operated fairly well, with the exception of certain mechanical difficulties, due primarily to high speed. In specific applications, they operated very well, but they proved too delicate to send out broadcast and their manufacture was dropped for a while.

In 1909, turbo-generators were again taken up by the Westinghouse Company. In this case, however, the construction was limited to sizes of 150 kw and lower. A large number of these

small units were put out and have been quite successful from the operating standpoint, but they were expensive to build, from the generator standpoint, compared with machines of similar capacities at much lower speeds and low in economy on account of low turbine speeds.

It was long ago recognized that the turbo-generator unit was a bad compromise between the most desirable turbine and generator speeds. In general, the highest practicable speed for the generator was much below the desired speed for the steam turbine. In practically all cases of actual turbo-generators, the engine was therefore operated at too low and the generator at too high speed. In turbo-alternators, the capacities and speeds were continually being increased, while in direct-current work the tendency, especially in larger capacities, was toward lower speeds. Obviously, this was going in the wrong direction, and there appeared to be little or no hope of carrying the turbo-generator into the large capacities. Obviously, the solution of this problem lay in some mechanical or electrical form of drive which would allow higher turbine speeds and lower generator speeds. In the electrical drive, a solution was obtained by substituting for the generator a very much higher speed alternator, the current from which was supplied directly to a rotary converter of any preferred speed. In a 500 kw unit, for instance, a 3 600 r. p. m. turbo alternator was used instead of 1 500 r. p. m. required with the direct-current unit. This enormous gain in speed was sufficient to offset, in cost and performance, the additional apparatus required. Moreover, the combination was much less delicate than the straight turbo-generator. A number of such sets was supplied, of capacities from 300 up to 2 000 kw. However, a mechanical solution of the problem was then brought forward in the Westinghouse floating gear, which solved the gear problem for very large capacities, and allowed high-speed turbines to drive moderate speed generators. In this way, turbines built for turbo-alternator units, which were about as high speed as practice would permit, could be connected to generators designed for motor-generator sets which were also usually of as high speed as best design would permit, as regards cost and good operation. Thus, with this gear, the best speed conditions for both engine and generator, could be obtained, and moreover, standard turbines and generators designed for other purposes could be combined in one unit—a very desirable condition from both the manufacturing and the commercial standpoint.

Quite a number of these geared sets in capacities from 500 to 3 750 kw have been built and put in operation. The results obtained have sealed the doom of the large direct-connected turbo-generator. In fact, they are so favorable that there is good reason to believe that eventually the geared sets will be carried down to sizes much less than 300 kw with very considerable gain in economy at least. This looks like a logical line of development.

Unipolar Generators

The saying that, "Happy is the country which has no history" may be paraphrased in the electrical manufacturing business, into "Happy is the company which has no unipolar history." Yet there was a time when the unipolar generator appeared to fill a long-felt want, namely, as large capacity turbo-generators. It was long ago recognized that the turbo-generator could not be carried to large capacities unless unduly low turbine speeds were used. Against this, the unipolar generator appeared to furnish a satisfactory means for getting direct-current in large quantities, and at commercial voltages, from very high-speed generators.

From the standpoint of size, weight and cost, the higher the speed of the unipolar generator, the more commercial it becomes. But from the current-delivering standpoint, which is the important function of the machine, the higher the speed the more difficult does successful operation become. The difficulty is not in making a machine which will hold together at very high speeds, but is almost entirely in making the current-collecting devices work satisfactorily at such speeds. In the unipolar generator, the voltage obtainable per conductor, that is, per pair of collector rings, is a direct function of the section of the magnetic circuit and of the number of revolutions of the machine. But the collector rings must surround this magnetic circuit, and therefore, the peripheral speed of the collector rings is also a function of the section of the magnetic circuit and the revolutions. Therefore, the voltage per pair of collector rings is related to the peripheral speed of the collector rings; and, unless a relatively large number of collector rings is used for ordinary commercial voltage, the unipolar turbo-generator is bound to have extremely high collector-ring speeds, practically between 12 000 and 20 000 feet per minute. By making the section of the magnetic circuit larger and reducing the speed in proportion, the peripheral speed of the collector rings may be reduced somewhat, as the periphery of the magnet does not in-

crease as fast as its section. However, this cannot be carried very far, in large capacity machines, without running into abnormal weights and costs. Therefore, in large capacity unipolar turbo-generators, it is not commercially practicable to get below certain collector ring speeds.

As already mentioned, about 1904 there was a considerable demand for large turbo-generators. The Westinghouse Company put out nothing above 500 kw, but the General Electric Company put out a few much larger sizes, such as 800 kw and even one of 1 700 kw for railway work. These larger machines, however, required such low turbine speeds as to be commercially unsatisfactory. Moreover, the generators themselves were not particularly satisfactory, being beyond the limits of practical design of those days. Therefore, the General Electric Company, apparently in looking for a substitute, took up the unipolar design for turbo-generator work. This did not appear to present any great difficulties, as the unipolar principle had been well proven out years before. A number of unipolar generators in capacities up to 500 kw, and even one unit of 2 000 kw were built. These machines apparently were very promising at first, but later a number of unexpected difficulties developed.

In 1896, and later, the Westinghouse Company built and disposed of a number of small three-volt unipolar generators for meter testing; but about 1906, a contract was obtained for its only large unipolar turbo-generator. This was a 2 000 kw machine, 260 volts, at 1 200 r. p. m. This differed from the General Electric machine in a number of respects, having a considerably lower peripheral speed at the collector rings, and using special bronze instead of steel in the rings. It turned out that these two differences were more or less fundamental in their effect on the operation. This machine was finally put into successful service after discouraging experiences,* and operated satisfactorily for several years. It has been shut down very recently, and is now held as reserve to a rotary converter transforming plant, which has taken its load. This change was not on account of any operating defects of this unipolar unit, but on account of very cheap power rates, a condition which has recently been responsible for putting many industrial and railway generating plants out of business.

The General Electric 2 000 kw unipolar generator showed difficulty in current collection. The collector rings were of steel

*"Development of a Successful Direct-Current 2000 Kw Unipolar-Generator" page 145.

and the peripheral speed was about 40 percent higher than on the Westinghouse machine. These conditions introduced certain fundamental difficulties which could not be overcome, and eventually this generator was replaced by an alternator which furnished current to a rotary converter.

These two cases practically end the history of the large capacity unipolar generator in America, for the alternator, with rotary converter, and the geared generator, as referred to under turbo-generators, have practically put the unipolar generator out of business.

AC-DC Generators

Both alternating and direct currents have been required from the same generating station at times, such as for railway service directly from the station, and for lighting or for transmission to remote rotary converter or motor-generator substations. Therefore, ever since both alternating and direct current have been generated in the same station, there have been propositions that both services be supplied from one generator. As early as 1893, the Westinghouse Company took a contract for two 150 kw generators capable of delivering 50 cycle alternating and 525 volt direct current from the same armature. These were 8-pole, 750 r. p. m. belted machines, and therefore were not unlike other belted machines of that time, in speed and capacity. The larger number of poles somewhat complicated the conditions, and made the commutation more difficult, due to the comparatively narrow neutral zones. It was recognized in the design of these early machines that separate excitation would be required on account of the alternating-current load, as it was well known at that time that self-exciting machines were very unstable when carrying inductive loads. Also, on account of the two classes of service from the same machine it was considered useless to compound the machine for direct-current load. In fact, it was pretty thoroughly recognized that in general the two classes of service could not be very consistently handled from one machine.

When these machines were put on test, some very interesting results were obtained. For instance, when an alternating inductive load was thrown off, the direct-current load conditions remaining unchanged, the voltage would rise possibly 30 to 40 percent, due to the fact that, as alternating-current machines, the magnetic circuits could not be highly saturated, as was then common

practice in direct-current work. With the high resultant voltage, there was liability of considerable flashing at the commutator. Also, when the direct-current terminals were short-circuited, the commutator developed the largest fireworks that the writer has ever seen from a small machine. This was due primarily to the separate field excitation and the high field ampere-turns compared with the armature. In the ordinary self-excited machine, there will usually be vicious fireworks momentarily in case of a short-circuit, but the machine quickly "kills" its excitation. In this separately excited machine, the field excitation was not killed in this manner, and if flashing or "bucking" was once started, it kept up the performance. This trouble was finally reduced by means of a special field circuit breaker which killed the field in case of excessive load.

These machines were so sensitive on the direct-current end that the writer advised against their shipment. However, they were so badly needed that they were sent out to help matters temporarily, and astonishing as it may seem, additional machines, exact duplicates of the first, were ordered from time to time. It developed that the power company used them principally for alternating-current work, the direct-current end representing reserve or emergency conditions for a railway plant. They were perfectly satisfactory as straight alternators, and they could have been used to supply direct-current if any emergency had occurred.

About two years later, the Westinghouse Company sold some belted a.c.-d.c. machines, in which the principal service was to be direct-current with some alternating-current to be taken for operating a rotary converter. This was not such a difficult condition, and proved satisfactory in service. The tendency in railway work, however, was toward engine-type generators almost exclusively and, of course, the engine-type a.c.-d.c. generator had to receive some attention. But here a stumbling block occurred in the frequencies and the usual engine-type speeds. With 60 cycles, for instance, an engine speed of 120 r. p. m. (which was high for a 500 kw unit, for example) would require 60 poles to give the desired frequency. But a 60-pole direct-current machine of 500 kw was commercially impracticable. The same held true for practically all engine speeds and generator capacities, so that the a.c.-d.c. 60 cycle engine-type machine was never considered commercial. A few 60 cycle high-speed belted a.c.-d.c. generators were sold, these being usually 60 cycle rotary converters modified into generators.

In 25 and 30 cycles, however, there were possibilities in engine-type generators and in consequence, a few of them were built. The Westinghouse Company furnished four 1 250 kw, 550 volt a.c.-d.c. generators with 32 poles for 94 r. p. m. Some 500 kw slow-speed machines for 25 cycles were also built. Quite a number of 12-pole, 250 r. p. m , 25 cycle and 14-pole, 257 r. p. m., 30 cycle, 500 volt a.c.-d.c. direct-coupled generators were built and put in service. Most of these machines were intended for railway service with both kinds of current, the alternating current being transmitted to rotary converter substations.

All the above were good operating machines, but more or less at the expense of abnormally large designs. They had to be made with exceptionally good commutating characteristics, for the armature reaction and field distortion were dependent upon the alternating as well as the direct-current loads.

Apparently, experienced designing engineers have never been wildly enthusiatic over the a.c.-d c. generator, for its interfering characteristics were against the machine. In consequence, other methods of accomplishing the same result in a more satisfactory manner, were given very careful consideration. With improvements in the straight alternator and in the rotary converter, it gradually developed that an alternator and a rotary converter could, in many cases, be built as cheaply as a corresponding a.c.-d.c. generator. When this stage was reached, the a.c.-d.c. generator, in most cases, had no real excuse for existing, and so it dropped out of sight commercially. Here is a case of a type of machine which at one time had good commercial prospects, but which is now entirely obsolete from the manufacturing standpoint. If anyone imagines there is any discredit attached to this situation, then the Westinghouse Company, which put out most of the a.c.-d.c. machines, will have to shoulder the greater part of it. The enormous development of the alternating-current power stations, with rotary converter substations, has put a number of very good lines of apparatus out of business.

Compensating and Commutating-Pole Machines

The commutating-pole machine is the latest big step in direct-current development. It is very closely allied to the compensated machine, although it may be noted that the latter came into use many years ago while the straight commutating-pole type was comparatively modern in its application. Crude forms of

compensating windings were proposed comparatively early in the electrical work. However, the more complete form in which the distributed compensating winding was used appeared about 1893. This was the Thompson-Ryan compensating winding. A line of direct-current generators, known as the Thompson-Ryan, was put on the market. However, compensating windings did not come into general use, apparently because the conditions under which they make their best showing did not exist at that time. The compensating winding possessed three advantages: (1), it helped commutating conditions; (2), it reduced the maximum voltage between commutator bars, with a given number of bars per pole, and (3), it allowed a higher no-load induction in the armature teeth. However, when the first compensating machines were brought out, none of these advantages were controlling—(1), due to the fact that engine-type generators then practically had the field, and in such generators as a rule, commutation was not a limit; (2), there were usually more commutator bars than were actually needed as regards maximum voltage between bars; (3), those slow-speed, low frequency machines usually had their armature teeth worked so very high that the elimination of the cross-magnetizing effect of the armature would not mean a very large gain in permissible flux, in many cases.

The real field for compensating windings in generators was in high-speed, high-frequency machines with a small number of commutator bars and with comparatively low teeth saturations, such as in the generators of motor-generator sets. But it so happened that when these began to reach their limits in capacity and speed, commutation was the first serious difficulty encountered, and the adoption of commutating poles overcame this, so that the field for the compensating winding was again narrowed. The field seems now to be limited largely to those machines in which cross induction is objectionable and where there is need for reducing the number of commutator bars per pole below what has heretofore been permissible practice. In consequence, the compensating winding has recently extended only to two new classes of apparatus, namely, very large motors and generators for reversing mills and steel plants, and high voltage generator work, in which there is difficulty in finding room for the requisite number of commutator bars without excessively high commutator peripheral speeds.

The commutating pole which has, during the past few years, come into such general use, is not a modern idea, as it was proposed about 1889 to 1890 in England. There was a field for it in

the early belted multi-polar railway generators, but before practical designs progressed up to the point of commercially using such a device, the engine-type generator came in, and this, to a great extent, did away with the necessity for the commutating pole. Thus the commutating pole idea dropped out of sight, and did not come back again until a real need for it developed. This was apparently in connection with adjustable speed motors having speed ranges of three or four to one. The occasion for such a speed range developed in connection with machine-tool electric drives. In some of the earlier machine-tool drives, a two-voltage, three-wire supply was used. With such a system, a shunt motor having an adjustable speed range of two to one by means of a shunt field could be given a four to one total speed range by means of the three-wire supply system. This, however, was a rather complex arrangement, taken as a whole, and was not of general application, and it soon became evident that a four to one speed range in the motor itself, with the standard two-wire or one-voltage supply system, would be much simpler and of more general application. This, therefore, led to the four to one adjustable speed motor for such service.

Various schemes were tried for building such motors, among others being commutating poles. The great difficulty, of course, was to maintain good commutation at the highest speeds and weakest fields. Eventually the commutating pole furnished the simplest solution from the design standpoint and was adopted by a number of the different manufacturing companies, the Electro-Dynamic Company apparently being earliest in the field. However, the use of commutating poles was limited principally to such special service until occasion arose to apply it on railway motors. The railway motor had been developed into a well-established piece of apparatus, with apparently only a few serious defects, among which was an occasional tendency to "buck over," apparently without sufficient reason in some cases. This was credited partly to "breaking-and-making" the circuits when passing over gaps in the trolley system, etc. Under such conditions it was found that the motors would take a comparatively heavy current rush which sometimes would cause flashing. Early tests developed the fact that a railway motor equipped with commutating poles was apparently much less sensitive to flashing than the standard type. This was a promising idea and was quickly followed up. This was one of the reasons for adoption of commutating

poles in railway motors, but there was quite a number of other reasons, possibly none of them controlling, but, taken together, they made quite a showing. In an extremely short time after commutating poles began to be talked about for railway motors they became pretty much a "fad," and this assisted in their adoption. This revolution was accomplished very quickly, and within about two years after they were first considered seriously, practically everything in the way of new railway motors was of the commutating-pole type. But this was one of the fads that lasted, for there was much more merit in the commutating poles in railway motors than the public first appreciated.

The quick revolution in railway work accomplished by commutating poles had its effect upon all other classes of moderate and large sized generators and motors. In some classes of apparatus where the commutating pole was embodied it was not actually needed, such as in small slow-speed generators. However, in other classes of machinery, such as high-speed generators, it practically revolutionized design in a few years' time by allowing the use of much higher speeds for a given output, or much larger output for a given speed. This was true particularly in those cases where commutation was the real limit. The commutating poles, in removing this limit, or greatly increasing it, allowed radical changes in the design.

It has long been known that maximum outputs for a given amount of material meant high armature ampere-turns for a given size of armature. Nevertheless, such constructions could not be carried to their logical limits in the usual non-commutating pole machines, due to limitations of commutation. However, the use of commutating poles overcame this difficulty, and thus, to a considerable extent, revolutionized the design of moderate and high-speed motors for general purposes. A leading example of this is found in the Westinghouse "SK" line of motors, which was designed with commutating poles to use the material throughout to the very best possible advantage. This line was designed with a view toward future tendencies, and was apparently considerably ahead of the times when it first came out, judging from some of the criticisms which were brought against it. At the present time the commutating-pole construction is used in practically everything in direct-current apparatus that the Westinghouse Company builds, with the exception of very small apparatus. Many of the other manufacturing companies can say the same.

Since the commutating pole has come into general use, generators and motors for some very extreme applications have been carried out. Very large capacities of generators at speeds undreamed of with non-commutating-pole machines have been carried through successfully. For example, a 3000 kw, 600 volt, 375 r. p. m. generator, forming part of a flywheel motor-generator set, was furnished by the Westinghouse Company for the Illinois Steel Company for operating a large reversing mill. Also, a number of 3 500 kw, 300 r.p.m., waterwheel driven generators of 600 to 700 volts were furnished by the General Electric Company for an aluminum plant at Niagara Falls. These two examples represent about the extremes in direct-current design that have yet been built; for, while larger capacity machines have been or are being built, yet they are for much lower speeds. In these two extreme examples, furnished by two different manufacturers, there are certain superficial resemblances. For example, in both cases, the armatures are of the double commutator type, both commutators being connected to the same winding.

In slower speed machines, some 3 750 kw, 270 volt Westinghouse machines at 180 r. p. m. have been geared to 1 800 r. p. m. steam turbines. These are possibly the largest current-capacity machines yet built. The field for large direct-current generators now appears to be limited principally to electro-chemical or electrometallurgical work where direct current is necessary, or to special applications, such as certain classes of mill work, etc. Some comparatively large generators have been built for motor-generator sets; but the synchronous booster rotary converter now seems to be making considerable headway in that special field where the motor-generator formerly stood alone, namely, where fairly wide variations in direct-current voltage are required.

High Voltage Generators Without Commutators

This is a chapter which should possibly be recorded simply on account of the persistency of its subject, and of the vast amount of unproductive work which has been expended upon it. This work, however, has been of more or less educational value, on the theory that as much is learned through failures as from successes. The production of unidirectional high voltage in generators without commutators or a multiplicity of collector rings, has been one of the "will-o'-the-wisps" of the electrical field. Apparently there are only a few engineers and analysts who have gone into this

problem so thoroughly that they recognize certain fundamental reasons why such machines cannot be built.

This problem may be compared, in some ways, with the perpetual motion fallacy. A perpetual motion scheme may be made so complicated and may involve so many principles and combinations that it is very difficult to put one's finger on the real fallacy; yet, if the law of conservation of energy is brought to bear upon it, the details of the scheme need not be considered at all, for this one fundamental law condemns it utterly, regardless of methods or means involved. In the same way, in the direct-current machine without a commutator, certain fundamental principles of flux cutting and e. m. f. generation are sufficient to condemn all machines of this sort, regardless of their type or construction. In the final analysis they usually come down to one effective conductor, or turn, per pair of collector rings, which is the well-known unipolar generator. However, the fundamental principles are difficult to make clear to the inexperienced, just as it is hard to convince some people that the law of conservation of energy holds good over the whole finite scale, from the practical standpoint. Therefore, the writer anticipates passing upon such schemes in future, just as he has done for some 25 years past, and he, coincidentally, will be obliged to dampen many bright hopes.

As indicated, the fallacies are principally due to misunderstanding of fundamental principles. For instance, a favorite scheme is to have the "magnetic lines" of the field move across the conductors, or vice versa, generating e. m. f. in one direction, and then have the lines closed back on themselves through some path which the conductors do not cut; not recognizing that, as the magnetic lines are closed circuits and the electric circuit is also a closed circuit, the lines cannot be cut once unless they are cut twice, if the action is to be continuous. The second cutting is always such as will generate e. m. f. in opposition to the first, and the only way to avoid cutting twice is to interpose some relatively non-moving or non-cutting part, which means two sliding contacts for each effective turn. This, of course, leads at once to the usual unipolar generator with one turn for each pair of collector rings.

As another instance, a common mistake has been to assume that, as the movement of the coil across fluxes or fields of alternate directions or polarities will give an alternating e. m. f., therefore, by reversing the fields at the proper rate, the armature e. m. f. will

be correspondingly reversed, thus making it unidirectional; whereas, in fact, it is still alternating, but of double frequency.

Other schemes involve "inductor" alternator constructions, with a view to obtaining half waves, or those of only one polarity, thus giving a pulsating unidirectional e. m. f. In such schemes the various transformer actions and the reverse cutting of the flux by the conductors are usually overlooked. Still other schemes are dependent upon the assumption that magnetic lines may be open or discontinuous; or, if continuous, may be stretched or lengthened indefinitely. Again, combinations of several or all of these ideas may be involved in the same proposed device, thus making a lucid explanation almost an impossibility. One of the most amusing schemes, which not infrequently appears, is where the apparatus generates a true alternating e. m. f., but in which the inventor has followed the action only through one e. m. f. wave, and overlooked the rest of the cycle.

All told, probably hundreds of thousands of dollars have been expended on this general fallacy, and doubtless many more thousands will be expended, just as in the case of perpetual motion. Moreover, much valuable time has been expended by those who did not believe in the possibility of such apparatus in showing wherein individual schemes submitted to them are not operative. The writer probably has been requested, two or three times per year on an average, to make a careful analysis and, in some cases, a full written report on schemes of this nature, which have been submitted to the Westinghouse Company. In fact, he has repeatedly threatened to prepare a printed form which could be used as a "blanket" report for all such cases. However, the fact that many of these cases come from "very good friends" apparently precludes such procedure.

Conclusion

As will at once be noted by any "old-timer," this history is far from being a complete one. The writer's endeavor has been to cover those points within his direct knowledge and experience which have had an important effect on direct-current generator and motor development; in other words, he has attempted only to hit the "high spots." If all the interesting sidelights, incidents, etc., within his own experience were to be included it would have extended this article to triple length, possibly, and it would have become much more reminiscent than historical. This article has

been made very broadly impersonal, as due credit cannot be given to all who have expended so much time and energy in bringing the development up to its present high stage. Occasionally personal references have been included, partly to break up the historical tenor, and partly to counteract any impression which may have been created, wholly unintentionally, that the writer personally, or the company with which he is associated has been the only active participant in this great development. Much of the history covering the inside story of direct-current generator development has never been recorded and will eventually be lost. If a few of the ancient mariners of this sea could be induced to tell their tales it would be a boon to the younger generation. If the writer has aided even a little in preserving this early history, he feels thoroughly repaid for his effort.

THE DEVELOPMENT OF THE STREET RAILWAY MOTOR IN AMERICA

FOREWORD—The author took an active part in some of the earliest commercial successful electric railway developments and has been in close touch with much of the later work. His direct knowledge regarding details of development by companies other than the one with which he is identified is, therefore, necessarily limited, to a certain extent. No claim is made that this article covers the history of all railway motors. It is rather the history of the author's own experience in this very interesting field. The present article is limited to street railway motors and no attempt is made to cover heavier service as represented by interurban and main line railways. Neither are controllers and control systems more than merely touched upon.

This article was first published in the Electric Journal.—(ED.)

RAILWAY motor development in America began back in the early 80's but much of this was of a purely pioneer nature and, while it left its impress, in most cases it was not a lasting one. On the other hand, certain of this early pioneer work led directly to the commercial railway motor of the later 80's.

Principal among the pioneers in this work may be mentioned —Van Depoele, Henry, Daft, Bentley-Knight, Sprague and Short. Some of the railway systems brought out by the early inventors simply flashed up for a short time and then disappeared. Others came and, through merit, stayed until forced out of the field by later developments, many of their good points being embodied in the later systems. The Van Depoele system, with its under-running trolley, left its impress on the future systems in the form of the under-running trolley itself, which has been used almost universally since. Professor Short, with his series system attracted some attention for awhile, but being defective in certain fundamental principles, this system disappeared in favor of the parallel system, which Short himself later adopted. The Sprague system, which came a little later than some of the others, was along more nearly correct lines. It contained certain good fundamental principles; it persisted longer than the other early systems, and eventually established electric propulsion as the coming system of traction for street railways, etc. This will be referred to more completely under the description of railway motors.

Railway Motors

Practically all the early railway motors which were commercially successful were of the double-reduction gear type, i. e., there were two sets of gears between the armature shaft and the car axle. There were two reasons for this, namely, the comparatively slow speed of the cars of those days, and the high speed of the motors, necessitating something like a ten-to-one speed reduction. In most of these designs the motors themselves were suspended from the car axle and were connected thereto by means of spur gearing. In a few special instances attempts were made to drive the axles through bevel gears, one motor being connected to two axles. None of these survived. Also, chain drive was used on the early Van Depoele system.

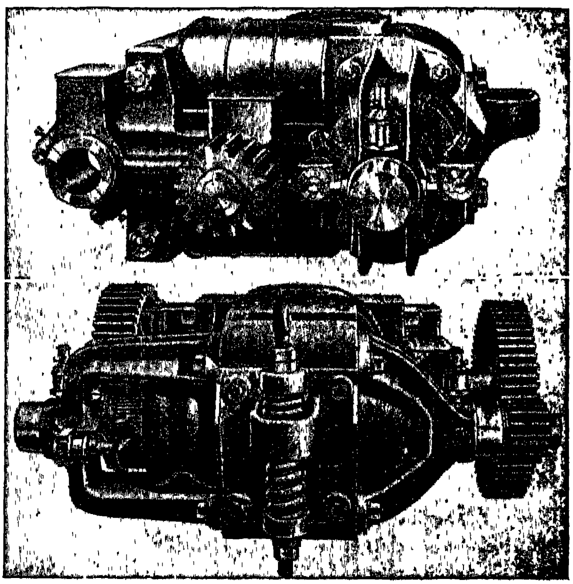


FIG. 1—SPRAGUE DOUBLE REDUCTION MOTOR 1889

By 1889 the electric railway had become quite firmly established. Even at this early day the most successful systems had certain points of similarity, which apparently had some bearing on their success. At this time, the Thomson-Houston (a development of the Van Depoele system), the Sprague (Edison Company) and the Short (Brush Company) systems were at the fore and all were

apparently quite successful. Early in 1890, the Westinghouse Company entered the field with a street railway system, thus making four principal manufacturers. Thereafter for several years these four systems were the leading ones on the market. Gradually two of these dropped out, or combined with others, leaving the General Electric (Thomson-Houston and Edison) and the Westinghouse as the only large manufacturers. Therefore, the following description will be confined largely to the motors of the four earlier systems and the two later ones.

Sprague Railway Motor

The Sprague electric railway motor system of 1888 to 1890 was unquestionably the most perfect one of that time from the standpoint of control and economy of operation. This was due principally to certain fundamental features of design, which had been carried to the utmost. This motor was of the two-pole type. The armature was of the surface-wound type with several layers of wire. It is obvious that such a motor was inherently poorly protected and, from the present standpoint would be considered an extremely doubtful piece of mechanism to place under a car. However, in those days, all other makes of motors were just as questionable and, therefore, this motor did not suffer by comparison.

The interesting feature about this motor was in the method of starting and speed control. The field structure was made of a good grade of wrought iron of high magnetic permeability. The field coils were wound in three sections of different sizes of wire and different numbers of turns and the field windings were so proportioned that, with all the field coils in series at start, a heavy torque was obtainable with a very small starting current, thus avoiding overheating the fields without the use of a starting rheostat. However, it should be said that, with all the field coils in series, the combined resistance of the armature and field was sufficient to fix the starting current at a relatively small value. Following the series starting position, by series-paralleling of the field coils, various combinations of speed were obtainable up to the maximum desired. Here was a system where all starting and controlling was done without external rheostats, a very economical method of operation and one which has possibly not been exceeded in any of the later commercial direct-current methods of operation. This was due largely to the relatively high speed of the armature of the

double-reduction type and to the fact that the field magnetic flux could be worked over a very wide range, while the total motor capacity was small compared with modern practice. These favorable conditions disappeared largely in the later, lower speed, single-reduction motors.

While this early Sprague motor was a very fine one from the viewpoint of economy of power, yet according to the writer's experience, it did not have the ruggedness for emergencies found in some of its competitors. The very element which made it so economical, namely, the series-parallel field windings and the absence of a rheostat, made it more delicate in emergency conditions which required abnormal currents for prolonged periods; such as pushing snow plows, for instance, during severe storms. In some cases the Sprague motor proved very inferior to some of its competitors, due to overheating when running at low speeds. Nevertheless, with all of its weaknesses, this Sprague double-reduction motor must be considered as the high class one of its day.

The Thomson-Houston Motor

In general, the Thomson-Houston motor was of the same general type as the Sprague. The magnet core was of wrought iron, or equivalent material. The armature was of the usual surface-wound type. Unlike the Sprague motor, speed control was only partially obtained by varying the field strength. The field was wound with loops or taps brought out near the middle of its length. For starting and acceleration, the full field winding was used with a rheostat in series. To accelerate, the rheostat was cut out gradually and for still higher speed, only part of the field winding was used, the other part remaining idle. Thus there was no true series-paralleling of the field windings. This method of operation, therefore, was less economical than the Sprague arrangement but, on the other hand, the proportions of the field winding and the rheostat were such that the motor could stand more severe conditions during starting and acceleration. The field magmetic circuit was apparently much more highly saturated than that of the Sprague motor, resulting in a flatter speed curve. In consequence this motor would run somewhat faster than the Sprague on heavy load, and was considered by many operators as a better hill climber, simply because it ran faster up hill. Due to its lower saturation, the Sprague motor tended to drop off very considerably in speed on heavy grades and this was considered an evidence of

weakness, that is, of lack of power; whereas, in fact, it was a real merit in those days of limited power supply. The range of current taken by this Thomson-Houston motor, due to its flatter speed characteristics, was apparently considerably greater than that of other types of railway motors. The commutation on this motor was apparently very good compared with the Sprague motor. In fact, the latter, according to the writer's experience, appeared to be one of the poorest commutating motors on the market. Nevertheless, due to its special method of control and the consequent

FIG. 2—THOMSON-HOUSTON DOUBLE REDUCTION MOTOR—F-30

smaller currents required, this poorer commutation did not seem to have as harmful effects as one would infer from looking at it. In other words, the commutator of the Sprague motor had about as good life as any of the others.

One thing that counted against good commutation on these early motors was the extremely heavy mica between commutators bars. One-sixteenth inch mica was not at all uncommon on such motors and when trouble developed at the commutator, there was frequently a cry for thicker mica and, as a consequence, the thicker the mica the greater the trouble. This persisted up into the later motor practice and was a source of much trouble for several years.

The Short Motor

In construction, the Short railway motor was a close relative of the Brush arc machine, that is, its magnetic circuit and other parts were arranged very similarly to that of the arc machine. A disc armature was used with pole faces presented at the sides of the armature. The early machines were of a two-pole type and later this

general construction was developed in four poles in connection with later Short systems. The armature of this Short motor was of a toothed type, this also being apparently a development from the Brush arc machine. It is questionable whether the teeth on this armature were proportioned for magnetic purposes or for mechanical. The teeth were few in number and the slots between were quite wide. Magnetically the arrangement might be considered as some improvement over the surface-wound type, but the proportions were not such as would be considered effective, even in the true slotted types of armatures which followed two or three years later.

This Short type railway motor contained a number of more or less fundamental defects, which in the end were sufficient to rule out the type. In the first place, due to the disc type of construction and side poles, there was a tendency for strong unbalanced side pull between the armature and the pole pieces, and strong thrust collars were necessary to overcome this. On account of this

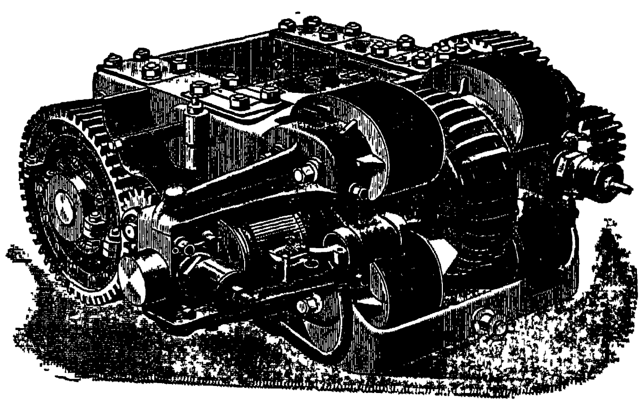


FIG. 3—SHORT DOUBLE REDUCTION MOTOR—1890

arrangement no end play was permissible, as in ordinary railway motors. In the second place, the method of connection between the commutator and armature winding was a very awkward one, since the armature leads had to be carried radially to the shaft and then along the shaft to the commutator. In the third place, with this general construction, a non-magnetic spider had to be used, as a rule. This meant a construction which was not as solid or as durable as was obtainable with the cylindrical drum type of arma-

ture with the laminations pressed directly on the shaft or upon a cylindrical supporting spider.

Even with all these defects this type of machine was continued for several years and was carried into the single reduction type and into the gearless, when the construction was somewhat simplified by the use of four and six poles respectively. However, the type was destined to disappear due to fundamental defects, and apparently only the persistency of Professor Short, who originated it, kept it going as long as it did. Eventually Professor Short himself abandoned the type, when he put out the Walker motor, which will be mentioned later.

Westinghouse Motor

The remaining double-reduction motor, which made any considerable impression on the railway field, was the Westinghouse. This was brought out in the Spring of 1890, somewhat later than the other systems mentioned. In general type, this motor was quite similar to the Sprague and the Thomson-Houston. However, the field core was of cast iron and the motor was, therefore, somewhat heavier than its competitors. The armature was surface-wound and similar to almost all railway motors of that time. The field winding was arranged in two coils without metal "bobbins," with different sizes of wire and different numbers of turns. For starting, all field windings were in series and the rheostat was connected in series. For higher speed the smaller winding was cut out. Obviously, this arrangement was electrically very similar to the Thomson-Houston.

The principal differences were in details of the mechanical construction. The fields were hinged to the supporting yoke in such a way that they could swing back to give more easy access to the armature. Also the gears were enclosed in gear cases which were filled with lubricating grease. The purpose was to overcome the very objectionable noises of the double reduction gears. Anyone who is familiar only with the present gear noises from traction motors can have no comprehension of the fearful racket some of the double-reduction equipments made, especially after the gears had worn badly. At night, when other noises had ceased to a great extent, the electric cars could be heard, in some cases, at a distance of one to two miles.

On many of the early double-reduction equipments cast iron gears were used and, as a consequence, stripped gears were not

uncommon. In those days cars were operated under conditions which no one would dream of attempting in these times. In one case, in the writer's experience, a track was being repaired in a certain part of Allegheny City and the only way to get around it was to run up a parallel street and part way over a cross street to the end of the track, which was about thirty feet from the original track. This intervening section, paved with rough cobble stones, was overcome by getting the car up to considerable speed

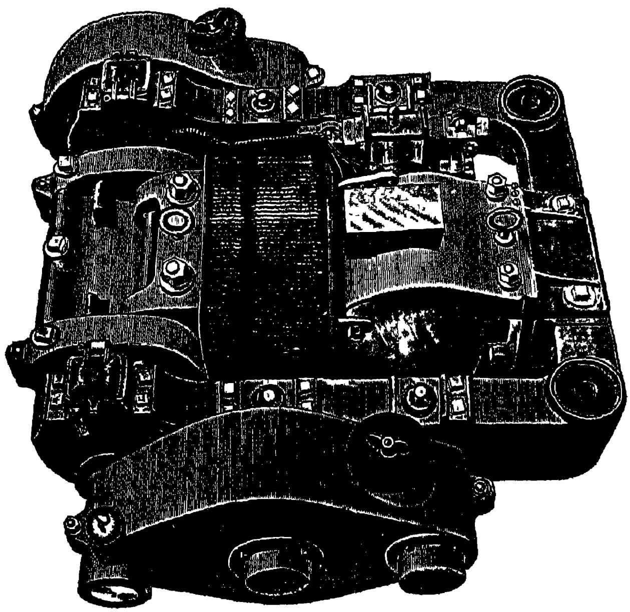


FIG. 4—500 VOLT WESTINGHOUSE DOUBLE REDUCTION MOTOR—1890

and running across the space by means of inertia. If the car did not get across, then a long wire was carried from the controller on the car back to the end of the truck and thus a "ground" was obtained for covering the rest of the way. In one instance, a car was stalled in this section and the motorman left his controller on "full" position while he carried his conducting wire back to the end of the track. Upon touching the rail, the car did not move out of its steps, so as to speak, but simply gave a jerk and the gears were stripped.

The Westinghouse double-reduction motor was made of cast iron, but its operating characteristics were quite comparable with

the other systems, except the Sprague. However, although a considerable number of these motors were put out in 1890, the writer, along with certain other engineers of that time, did not believe that any one of the then existing railway systems was final, due primarily to the fact that the motors were too susceptible to injury, not being sufficiently protected in view of their location under the car. It was believed that it was merely a question of time when all such motors would have to be rebuilt. The first Westinghouse motor was put in service in Allegheny, Pa., on July 3, 1890. This date is given to indicate the short time which elapsed before the writer, who had been instrumental in getting out this Westinghouse system, undertook to get out a radically different system to supersede it.

General Trend of Development

The above brings us up to the period when the single-reduction motor was developed. The double-reduction motor very quickly disappeared from the market after the single-reduction arrived, but it must be said that the double-reduction motor, and the early system as a whole, left its impress on the future development. There were several features in this early development which survive even to the present time, such as the use of carbon brushes, series-wound motors, motors suspended from the axles and geared to them, enclosing gear cases with grease lubrication, mummified field coils, under-running trolley, platform controllers, etc. The fact that a number of these features have survived in very much their original form indicates that they were fundamental in their nature. The early designers of such systems must be given credit for a quite comprehensive knowledge of the real problem of electric traction. Their short-comings were more in their inability to construct, than in their lack of knowledge of the correct principles.

Those early days were times of experimentation by the operators as well as by the manufacturers and it was not an unusual thing for a small electric system to have two or three different types of equipment, and in one case in a small system near Pittsburgh having seven cars total, there were five different kinds of equipment at one time. Furthermore, the operator was rather proud of the situation. In this early work there were a number of points which were taken very seriously in those days, but which, from the present viewpoint, are rather amusing.

For example: The earth was considered as being of negative potential and, therefore, many engineers (or so-called engineers) held the opinion that the positive terminal of the motor could not be connected with safety to the ground side as there was danger of a short-circuit. The writer spent many weary hours attempting to show some people the absurdity of this opinion, but generally without success.

Also another subject on which there was considerable controversy was that of large-diameter vs. small-diameter armatures. Many people contended that even with the same horse-power and speed a large diameter armature necessarily gave more tractive effort than a smaller diameter.

There was also much discussion concerning the speed and power characteristics of the various motors. Certain makes of motors ran faster up hill than others. The Sprague motor, for instance, was a slow hill climber; on the other hand, the Thomson-Houston double-reduction motor was a fast hill climber and the Westinghouse was in between. As a rule, most people believed that the Thomson-Houston motor was, therefore, a more powerful one than either of its competitors. The writer had quite frequent contentions that the Sprague type of motor, with its drooping speed characteristics, was more nearly ideal for railway work than the Thomson-Houston with its flatter speed curve. His claim was that the drooping speed characteristics called for a more uniform and a lower average current from the generating system, and therefore, required less generating plant. He contended that the place to make speed was on the level and not on the hills. Apparently this argument has never been definitely decided in favor of either viewpoint, but today it is generally recognized that the steeper speed characteristic is a more economical one as far as the generating or transmission system is concerned.

In comparing the merits of these early types of motors, a not unusual test was to couple cars with two different makes of equipments, end to end and then determine which could outpull the other, starting from "rest." Of course, a good deal depended upon the skill of the motormen, but in many cases those motors with drooping speed characteristics had the advantage, and therefore, according to this test, were more powerful, although when it came to climbing hills they were supposed to be less powerful. Here was a contradiction which puzzled a great many people.

One interesting feature in connection with the early motors may be dwelt on more extensively, namely, the use of the series motor. Very early in the development, shunt motors were tried but it was soon recognized that they did not meet practical conditions, and the series motor was adopted exclusively. However, in the use of the series motor itself there were certain differences in practice. For instance, most of the railway systems paralleled the field windings and the armatures, independently. For reversing it was necessary to bring out leads between each armature and its field windings, and the field windings of the different motors were permanently paralleled with each other. The same was true of the armatures. Then by means of one reversing switch all the armatures, or all the fields, could be reversed. In the Thomson-Houston system, however, the different field coils and armatures were not paralleled with each other, but separate reversing switches were supplied for each motor. Obviously this required more wiring and reversing switches than the other systems and was a subject of much criticism. But, this arrangement was fundamentally correct, and has come down to the present day. The other methods, with paralleled field coils, were subject to the difficulty that there could be greatly unbalanced currents in the armatures, where the magnetic fields were not of equal strength; whereas, with the Thomson-Houston motors there could only be unbalanced currents between the motors as a whole and not between individual armatures, and any unbalance in the current in the field coils tended automatically to correct the difficulty.

In the double-reduction motors, with their excesssively large air-gaps compared with later practice, differences in the magnetic properties of the materials did not count for much because such a large percentage of the field magnetizing force was expended in the air-gaps. However, when it came to the later single-reduction motors, with their smaller air-gaps and higher saturation in the cores, the fallacy in the parallel arrangement of the field coils began to show up quite early.

Single Reduction Motors

In August, 1890, the writer began work on a radically new type of railway motor of only about one-third the speed of the ordinary motor, with a view to using only one gear reduction between the armature and axle. In going into this matter from the electrical and magnetic standpoint, it soon developed that the

surface-wound type of armature was impracticable. Furthermore, it became evident that a cylindrical type of field construction with inwardly projecting poles, such as was common in alternators in those days, would furnish magnetic conditions much better than any previous type, *provided more than two poles were used.* The writer then laid out a four-pole field construction with radial poles and external cylindrical type yoke, and with a slotted type of armature. It was at once obvious that such type of machine was inherently better protected than the ordinary construction, due to the external yoke. However, in this general construction one serious stumbling block appeared, namely, the fact that for accessibility only two sets of brushes were desirable with a four-pole armature. This appeared to be quite a problem, for apparently the only known solution was in cross-connecting the commutator at every bar, which was at that time a fairly well-known construction. This construction, however, appeared to the writer to be prohibitive and he, therefore, set out to devise some other arrangement, and in doing so developed the now well known two-circuit or series type of winding for "drum" armatures. A great deal of criticism appeared in connection with this winding, but the writer was nevertheless sure of the principle and felt confident that it was a correct solution of the problem, and his confidence was sufficient to carry it through to a test. Two trial motors were built of this general construction, in the Fall of 1890. In these two early motors the lower half of the field yoke, or frame, was carried out and upward, forming housings which enclosed the lower half of the field winding and shielded the armature from injury from below. The two brush arms were placed on the upper quadrants of the armature, making them more accessible.

The armatures of these two motors were of the slotted type, with ninety-five slots (one less than a multiple of the number of poles, on account of the two-circuit winding). At first, attempts were made to wind these armatures by hand, but it was quickly recognized that this would be a rather doubtful construction and the writer proposed machine-wound coils which were at once made up and tried on the cores. Various modifications were tried on these first sets of coils and one attempt was made to shape the coils in such a manner that they would all be exact duplicates and could be placed symmetrically on the armature, in two layers in the slots, one half of each coil being in the lower layer, the other half on top, just as in modern railway armatures. We succeeded in getting

about two-thirds of the winding in place in this manner, but then the end parts began to interfere so that we failed in getting the other one-third in place, and this experiment was temporarily given up. It developed later that a little more knowledge of the correct shape of the coil would have allowed a successful construction of this type, and thus one of the big steps in the later development would have been anticipated. However, after several weeks of experimenting, it was decided to put the machine wound coils

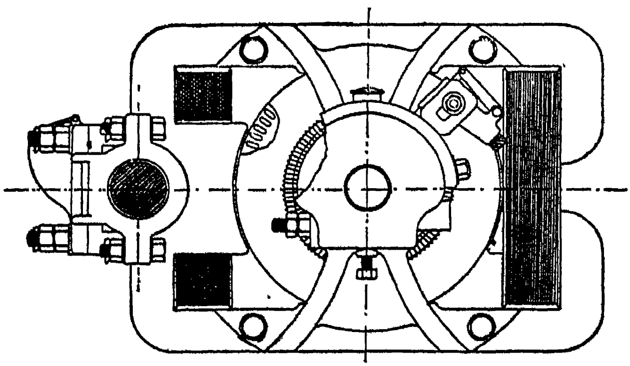


FIG. 5—DIAGRAM OF WENSTROM MOTOR—1890

on in two layers, hammering down the ends of the first layer in order to obtain end space for the second. With this arrangement, machine-wound coils were used successfully and the first two armatures were then wound in this manner, the writer personally winding one of them, although not an experienced winder.

The first completed machine was put on test and at the first trial, for a wonder, it started off and performed admirably over the whole range for which it was designed. The commutation was very good—unexpectedly so—as this was one of the points where trouble was feared. The two-circuit type of winding functioned as expected. By good fortune, one big departure from previous practice proved to be a stepping-stone to later work, namely, in these first machines the mica between commutator bars had been made only 1-32 in. thick; whereas, in double-reduction types of motors 1-16 in. mica was common practice. This "thin" mica, however, was objected to so seriously by almost everybody interested, that on the following motors it was changed to practically double thickness, but with disastrous results, as will be described later. This first Westinghouse single-reduction motor was tested

in the Fall of 1890, but was not considered quite ready for the market from the manufacturing standpoint, although in its electrical characteristics it had proven entirely satisfactory. It was decided to improve the motor by hinging the two halves of the cylindrical field to a supporting frame which carried the armature and axle bearings It was also decided to enclose more completely the lower half of the frame so that the armature and field would be protected from below. The motor was considered to be a very radical step, and it was thought advisable to take ample time in getting it ready for the market.

The Wenstrom Motor

Meanwhile, during this development, a situation arose which materially hurried up the work. The Wenstrom Company came out with a single-reduction motor which was heralded as being revolutionary in character. This motor was of the four-pole type with two salient and two consequent poles The armature was of a four-pole type. The armature winding was imbedded in holes or tunnels below the surface of the core. This armature was, therefore, one form of the slotted type. This machine created such interest that it was immediately decided to rush the completion of the Westinghouse motor for the next Spring trade, whereas, the former intention had been to continue the double-reduction motor for sometime to come. Moreover, the appearance of this Wenstrom motor immediately hurried all other motor manufacturers in their development of single-reduction motors. Apparently a number of them had already been working on this line, for their new single-reduction motors appeared so quickly on the market, that there was good reason to believe that they had already partly developed the machines before the demand came. Some of these motors were put on the market before they were properly developed and they proved to be merely makeshifts to be superseded soon by radically different types. This Wenstrom motor did not persist as it apparently contained certain defects which put it "out of the running" before it had gotten very far. It, however, hurried the situation very materially.

Westinghouse No. 3 Motor

The commercial single-reduction motor, which the Westinghouse Company put out in the Spring of 1891 was simply a further development of the experimental Westinghouse four-pole single-reduction motor already described. This motor immediately "took"

and a very large number (for those times) was sold the first season. In fact the demand for this motor was so pronounced that the company could not dispose of all of the double-reduction motors on hand partly or wholly completed

This No. 3 motor might be called the progenitor of the present practically universal type of direct-current railway motor. It contained a fairly large number of the fundamental features found in the present motors. Some of these may be classified as follows:—

1—Four-pole field construction with internal radial poles.
2—Symmetrical flux distribution, thus improving commutation.
3—Four coils all similar in size and shape.
4—Field coils without bobbins or supports, each coil being wound on a form and afterwards insulated.
5—Electrical parts naturally protected from below by the iron-clad construction of the magnetic circuit and frame.
6—Four-pole slotted drum type armature with open slots.
7—Machine wound armature coils, insulated before being placed on core.
8—Two-circuit or series direct-current armature winding, which is in almost universal use at present for railway work.
9—Saturated pole tips.

In addition the first motors built had 1-32 in. mica, which is now a standard for such work. However, on later No. 3 motors, the mica was changed to practically double this thickness, on account of the general insistence that 1-32 in. mica was utterly impracticable from the commercial standpoint. In the early days of the railway motor, thick mica was supposed to be the "cure-all" for all flashing troubles. If the mica did not wear fast enough, and lifted off the brushes, the machine sooner or later would spark and flash badly. The cry would be for more mica and, in some cases, thicknesses of as much as 1-8 in. were used, but without advantage as far as the writer could see, but the claim was made that the trade absolutely required such mica.

The writer and his associates yielded to this demand, with unfortunate results. The motors with thicker mica soon developed blackening and burning at the commutators, and the only direct remedy found for this was undercutting the mica. This was practiced on a number of the first motors put out, but was considered such an impossible practice that it was evident that some other remedy was necessary. Meanwhile the first two experimental motors had been running in regular service on the Second Avenue Line in Pittsburgh, and had developed no trouble whatever from commutator blackening or burning. After an exhaustive investigation of the conditions, the writer recommended going back to

the 1-32 in. mica, regardless of any demands to the contrary. A large number of the commutators with thick mica were then replaced with this thinner mica and the results were soon apparent in the fact that undercutting was unnecessary. This was conclusive proof that the thinner mica was a solution of the problem. However, it must be borne in mind that even the 1-32 in. mica of that early date (1891), was inferior to modern mica in wearing characteristics, as it was simply punched out of solid mica, the only sub-division being the splitting up of the mica segments into thin sheets and then assembling again in exactly the same form. "Micanite" or built-up mica did not appear until some time after this.

This No. 3 motor was very heavy for several reasons. It had a cast iron magnetic circuit; it had a relatively low gear ratio com-

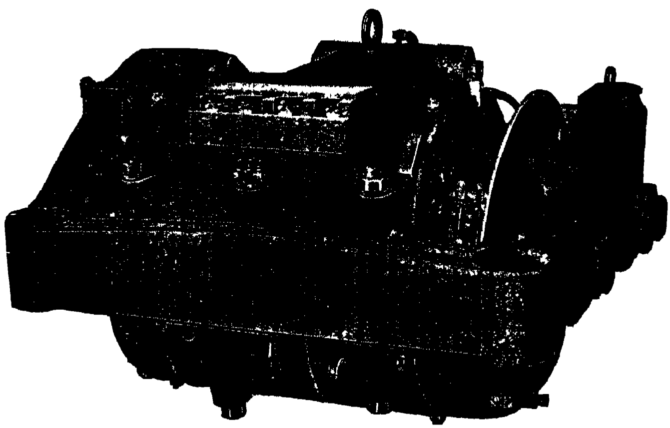


FIG. 6—WESTINGHOUSE No. 3 MOTOR—1891

pared with later practice, as it used an eighteen-tooth pinion and a sixty-four-tooth gear. In service, one difficulty soon showed itself, which had not been noticed in the corresponding double-reduction motors, namely, a very decided tendency to unbalance, in the armature currents of the two motors on a car. It was soon found that this was due to unequal counter-e. m. f.'s due to inequalities in field material, slight differences in manufacture, etc. On account of the relatively small air-gap, errors in manufacture produced an exaggerated effect. However, this difficulty was overcome by adjusting the air-gaps of the motors. It happened that this could be easily done by means of the two hinged halves of the fields. This arrangement permitted the motor to be opened slightly at the two

opposite joints, so that sheet iron liners of suitable thickness could be inserted in the joints of one motor until a suitable balance in the currents was obtained. It so happened that the Westinghouse Company had on hand a large stock of small compact ammeters built for the Waterhouse arc system, which had practically become obsolete. Little testing sets were made, using two of these ammeters mounted on a supporting base. These were furnished to the customers for use in balancing their car motors. Later the straight series arrangement of armature and fields was adopted and this unbalancing trouble was thereafter negligible.

When the single-reduction motors first came in, one of the subjects for frequent argument was in regard to the torque which such motors could develop. Many people claimed that inherently the single-reduction motor could not pull a car as well as the

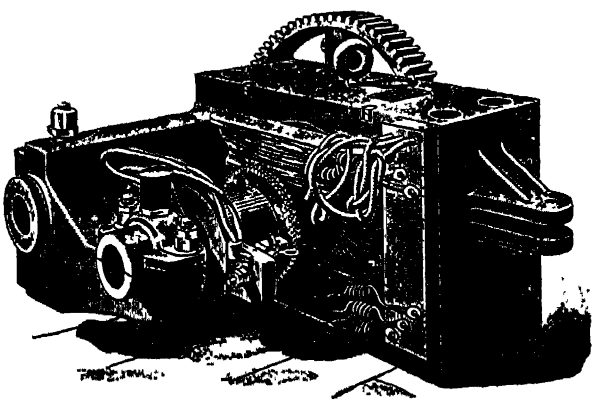


FIG. 7—THOMSON-HOUSTON SINGLE REDUCTION MOTOR—1891

double-reduction, even at the same horse-power rating, when developing the same car speed. This even went so far as to result in competitive tests. In one case in the writer's experience, a competitive test was run, about 1891, on the Second Avenue Railway under the impression that such a test would prove conclusively that the single-reduction motors did not have the required torque, and, therefore, would take enormous currents compared with the double-reduction. Local representatives of the Thomson-Houston Company agreed to, and took part in, this test, but apparently without any definite opinions as to which equipment would make the better showing. The test was continued during the greater part of one day, several round trips being taken over the whole length

of the system, and current and voltage readings were taken at ten-second intervals. An interesting result, noticeable during the progress of the test, was that the Westinghouse equipment seldom took less than 25 to 30 amperes when running light and seldom above 60 to 70 amperes under the heaviest conditions; whereas, the Thomson-Houston equipment at times took as low as 10 amperes and at other times up to 100 amperes. This was just what the writer expected, from his knowledge of the speed characteristics of the two machines, and he did not consider that the tests proved anything more than the general characteristics of the two machines would indicate. However, most of those present compared the *maximum* currents taken by the two equipments and drew the conclusion at once that the single-reduction was more economical. The writer, however, did not consider this a just comparison and took the trouble to carefully analyze the whole set of readings and found that the total power consumptions for the two equipments were so nearly equal that differences in the motormen's method of operation could easily account for any discrepancies. As a result of this test many people who heard of it revised their opinions of the pulling characteristics of the single-reduction equipment.

Thomson-Houston Single-Reduction Motor (S. R. G.)

This was one of the motors which was rushed on the market shortly after the Wenstrom motor appeared. It was a two-pole machine. The magnetic core was made of wrought iron in order to keep down the weight. The armature of this machine, according to the writer's memory, was of the ring type. From the electrical standpoint this motor was no improvement over the old double-reduction, and the ring armature in reality proved to be much poorer than the drum type used on the Thomson-Houston double-reduction motors. In fact, the only real merit of this machine was in its lower speed, thus allowing single-reduction gears. An attempt was made to protect this machine by an encasing or protecting sheet metal pan underneath. This pan was to a certain extent effective, but unless rigidly supported it made very noticeable noise, due to vibration.

W. P. Motor

It was soon recognized that the S. R. G. motor was not a permanent one, so that very soon a new type was gotten out, namely, the "W. P." (weather-proof). This was an enclosed motor and it was, from the electrical and magnetic standpoint, of a very peculiar design. There was but one field coil, placed above the armature. The armature itself was of very large diameter and weight and of the slotted type, with partially closed slots and the winding was of the ring type. The winding consisted of a copper ribbon threaded through the openings at the top of the slots and was wound in place by hand. On account of the magnetic arrangement, a non-magnetic spider was necessary. Also on account of there being only one magnetizing coil there was some stray field out through the shaft and bearings. This, of course, was minimized to a great extent by the non-magnetic spider. Possibly one of the worst features in this W. P. motor was the unsymmetrical commutating zone. Due to the type of the magnetic circuit, the flux distributions were not symmetrical under the two poles. Furthermore the armature reaction tended to distort the field quite seriously, thus affecting the commutating conditions. Very heavy mica was used in commutator and sparking was so bad that the life of commutator, in many cases, was only a few months. The armature leads had "eye" terminals to permit easy change of commutators.

In order to keep down the weight, this W. P. motor was either made of steel or an iron-aluminum alloy of good magnetic properties. This motor survived for a number of years, but due to inherent defects in its characteristics and construction it was doomed to eventual obsolescence. The ring type of armature and the unsymmetrical flux distributions were two conditions sufficient to condemn this machine, from the present viewpoint. However, it must be borne in mind that in those days certain features were considered very meritorious which now would be looked upon as prohibitive, the ring type of armature being one example. This W. P. motor had its place in the ultimate development of railway apparatus regardless of the fact that it did not survive.

Edison Single-Reduction Motor

The Sprague double-reduction motor was one of the best of its type, and persisted longest of any of this type. However, the Edison Company who had taken over the manufacture of the Sprague motor, finally recognized that the day of the double-

reduction motor was past and a single-reduction motor was then gotten out. This was a steel frame four-pole motor. The armature was of comparatively large diameter and, according to the writer's memory, was of the surface-wound type.* An attempt was made to retain some of the features of the Sprague double-reduction motor, by having commutated field coils, but due to the more highly saturated magnetic circuits, this was not very satisfactory.

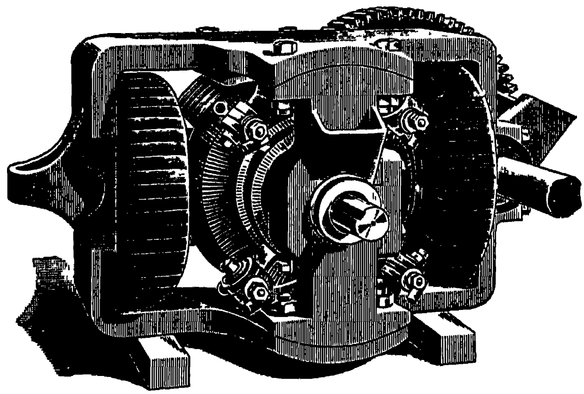


FIG 8—EDISON SINGLE REDUCTION MOTOR—1891

This motor had a comparatively short commercial life and it was evidently simply rushed into the market to meet the competition of other single-reduction motors.

THE SHORT SINGLE-REDUCTION MOTOR

Professor Short, early recognizing the trend of development, got out a single-reduction railway motor along lines somewhat similar to his former double-reduction. The principal difference was that this new motor was of a four-pole instead of two-pole type. The disc type of armature, with side poles, was retained along with most of the other characteristic features of the older motor. This motor attracted much attention, but as it possessed a number of fundamentally wrong features, such as a ring type of armature, danger from unbalanced side pull, etc., it was a type which was doomed to disappear eventually.

*Mr. W. E. Moore, Consulting Engineer, writes the author as follows:
"The old Edison S.R G motor had a Gramme ring armature; the coils being wound of flat copper ribbon in a toothed core. This motor was built in two sizes. The one which you illustrate in Figure No 8 was the smaller size, known as the Edison No. 14. The larger size was known as the Edison No 16, which was quite similar, except that the armature bearings were carried in arms projecting from the axle housing forward, instead of the vertical yokes and the consequent pole pieces were split vertically, with a hinge on top and bolted together at the bottom for removal of the armature."

In this early period of the single-reduction motor, the belief was held, rather generally, that the ring-type railway armature was essentially superior to the drum-type. As the Westinghouse Company never put out anything but the drum-type railway armatures and as, at different stages in the early development, several of the competing companies used the ring-type, the writer was "hard put" at times to defend his company's practice. Many and long were the arguments which he had on this score. At one time it looked, to an outsider, as if the ring-type was capturing the field. This was when the Short single-reduction motor and the Thomson-Houston "WP" were the principal competitors of the Westinghouse single-reduction. Both the former motors had ring-type armatures against the Westinghouse drum-type. However, practical operation gradually developed the superiority of the drum-

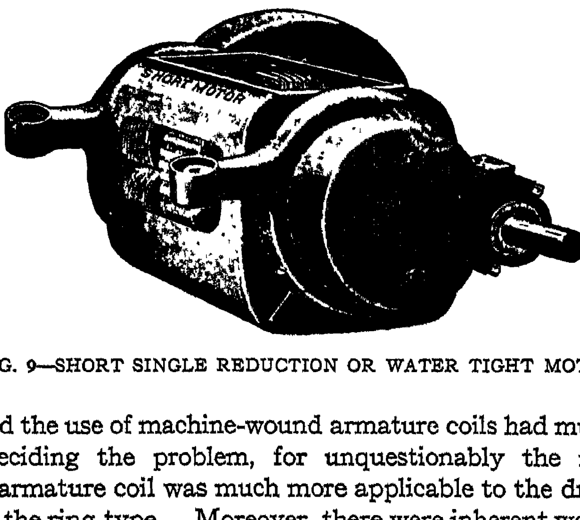


FIG. 9—SHORT SINGLE REDUCTION OR WATER TIGHT MOTOR

type and the use of machine-wound armature coils had much to do with deciding the problem, for unquestionably the machine-wound armature coil was much more applicable to the drum-type than to the ring-type. Moreover, there were inherent weaknesses in the ring-type, such as the use of non-magnetic spiders, methods of attaching the spider to the core, etc. In the light of present experience, it is surprising that the ring-type armature made as good showing as it did.

Gearless Motors

Following the success of the single-reduction motors, two of the companies, namely, the Westinghouse and the Short, attempted to make gearless motors along the same general lines as the single reduction type. The Westinghouse Company put out two con-

structions, one having four poles and the other having six, the latter being considerably lighter. However, both of these motors were too heavy and it soon developed that the gearless principle was not a satisfactory one for ordinary street car purposes, due largely to undue weight directly on the axle, and to the difficulty in removing an armature from the axle, in case it was necessary for repair purposes.

The Short Company built a gearless motor along the same lines as its single-reduction and tested it out in practice, but it was soon abandoned for the same general reason as the Westinghouse, namely, that the gearless principle was fundamentally incorrect for ordinary street railway service.

Further Developments of Single-Reduction Motors

As indicated, the Edison motor soon dropped out of the running. It contained nothing lasting in its type. Also, although it persisted longer than the Edison, the Short type gradually dropped out. Meanwhile the Edison and the Thomson-Houston Companies had combined and formed the General Electric Company. This company continued to develop its railway motors in the attempt to find something better than its W. P., already described. The Westinghouse Company also persisted in its development, principally with a view to reducing the size and weight of the No. 3 motor. The future development of the railway motors, therefore, lies almost entirely with these two companies.

The Walker Company, about 1895 or 1896, appeared on the market with a railway motor and did a very considerable amount of business until absorbed by the Westinghouse Company. The Lorain motor attracted considerable attention for a time, but was also taken over by the Westinghouse Company. Both of these were so nearly along the general lines of the Westinghouse, that they need not be considered as special types.

Later Types of Westinghouse Motors

After the No. 3 Westinghouse motor had proved to be commercially a very successful type, the writer turned his attention toward improvement in its general type without losing any of the more advantageous features. One of the features in the design of the No. 3 was the use of as many slots in the armature as there were armature coils and commutator bars. This was supposed to give ideal magnetic symmetry and, therefore, was assumed to be the

best possible arrangement. However, the writer in going over the magnetic principles and proportions of the motor, decided that by sacrificing magnetic symmetry to a certain extent, considerable gains could be made in reducing the dimensions of the machine. For instance, calculations indicated that by cutting the number of armature slots to half the number of armature coils or commutator bars, there would be an appreciable saving in slot space with a corresponding gain in iron section in the armature teeth which was one of the limiting conditions in the machine. However, this involved the use of two coils side by side per slot and, with a four pole machine it meant an unsymmetrical armature winding, for

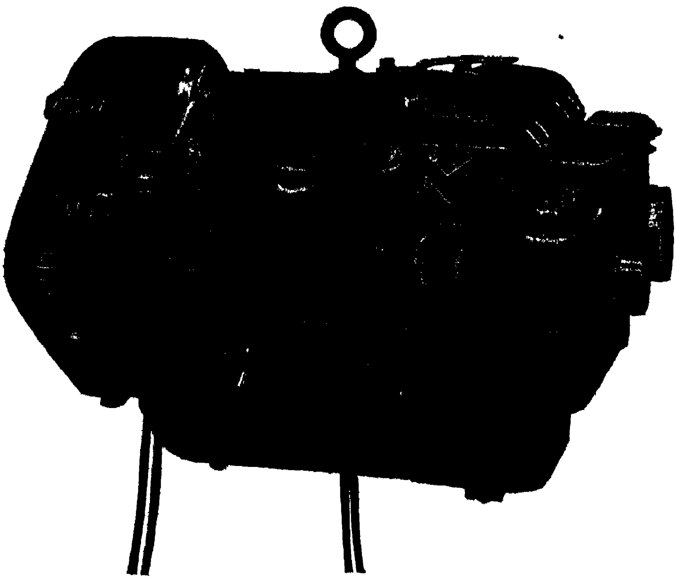


FIG. 10—WESTINGHOUSE NO. 12 MOTOR

with the two-circuit winding on a four-pole machine, an odd number of armature coils was necessary. This meant an idle coil, or idle coil space, on the armature. This was considered as detrimental in theory, but, on the other hand, it was believed that the wider armature slots with their lower self-induction, together with the much shorter armature core resulting from this construction, might compensate for some dissymmetry in the winding. This was only a theory, but it was thought worth while trying out. According to the calculations, with this construction together with higher speed due to increased gear ratio, the old No. 3 motor armature (keeping the

same diameter) could be shortened about 40 per cent and the field could be modified in proportion. This meant a very considerable reduction in size and weight and was well worth going after. A trial machine was built and tested and, instead of being materially poorer in commutation, it developed that the gain due to the wider slots and shorter core, more than offset any harmful effects of the unsymmetrical winding, so that the resultant machine was a somewhat better commutating, cooler, more efficient and much lighter machine than the No. 3. This was a somewhat startling result, but the tests showed conclusively that it was correct. It

FIG. 11—ARMATURE OF WESTINGHOUSE NO. 12 MOTOR

was then arranged to bring out a new Westinghouse motor to take the place of the No. 3. It was decided to go as far as possible in reducing the dimensions and weight of this machine and, therefore, the supporting or surrounding frame of the No. 3 motor was abandoned and extensions from the yoke of the motor itself, forming the end housings, were designed to carry the armature bearings. In this way a further reduction in weight resulted.

The Westinghouse No. 12 Motor

This new motor was known as the Westinghouse No. 12. In this motor the lower half of the field was enclosed by means of the end housings. The armature winding was of the formed-coil type, like the No. 3, arranged in two layers and with the end windings hammered down.

Very shortly after this motor was put out an improved form, known as the No. 12-A was brought out. This was quite similar in general to the No. 12. The principal improvement in the No. 12-A was in the armature construction. The armature core was ventilated, to secure increased continuous capacity and the arma-

ture winding was of the modern type with all coils of the same size and shape, and arranged symmetrically. The armature core of this machine was quite highly saturated at heavy load and this was found to materially improve the commutation. This No. 12-A motor was found to be quite superior to any preceding motors in its general characteristics, especially in its continuous capacity.

In its field construction it resembled the old No. 3, in the fact that it had cast iron yoke and poles and the field poles were cast integral with the yoke and were straight-sided so that the field coils could be slipped on directly over the pole tips. There was one feature in these motors and their variations which materially af-

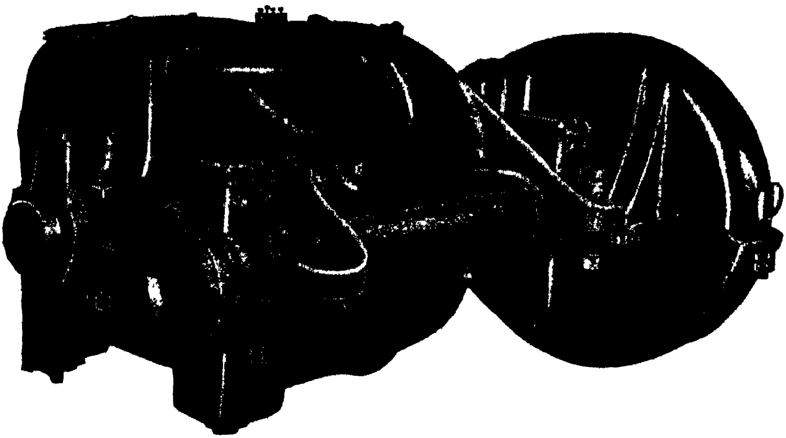


FIG. 12—WESTINGHOUSE No. 38 MOTOR

fected their operation, but which was not fully appreciated at the time they had been designed, namely, the effect of the cast-iron poles in improving the commutation. The pole tips of these motors, as a rule, were somewhat smaller in cross-section than the pole bodies or cores and, thereforre, there was quite high saturation in the pole tips, particularly at heavy load. This high saturation had very much the effect of the "cut-away" pole corners, used later on laminated pole machines.

The Westinghouse No. 38 Motor

Recognizing that in the No. 12-A motor the general type of construction had been carried as far as possible, due to the limitations in the cast-iron field structure, it was decided to attempt a different field construction, in which the limitations in design could be pushed up very considerably. This was embodied in the

Westinghouse No. 38 motor. This motor, in general type, was similar to the No. 12-A, except that in the first motor built, the field was made of solid cast steel, both poles and yoke, with the poles cast integral with the yoke. This construction allowed very materially higher field fluxes than in the former motors, so much so that again the armature teeth became the limit in saturation. Therefore, in the armature three coils per slot were used instead of two, thus gaining in armature tooth section. This, the writer believes, was the first use of the three-coil-per-slot arrangement in railway motors. This first No. 38 solid-steel-pole motor showed unduly high losses due to the solid-pole construction. Immediately it was changed to laminated pole construction with the poles cast integral with the yoke. This apparently was the first use of laminated poles with steel yokes, in street railway motors.

This No. 38 motor represented, with minor differences, the present type of railway motor. One principal difference was in the cast-in laminated poles, instead of the present practice of bolted-in laminated poles It had ventilated armature windings and relatively high saturation in the armature core to help commutation at heavy loads. Also with the three-coil-per-slot arrangement, with four poles, a more symmetrical armature winding was possible than in the two-coil-per-slot No. 12-A motor, there being no idle coils. In the former motors the bearings were lubricated with grease, as was common practice in all motors at that time. However, when heavier and more difficult service was encountered, as was the case with the No. 38, which was of higher capacity than most of the former motors, it was found that the grease method was not very effective. This resulted in a modification which provided a felt wick and an oil well under both the armature and axle bearings, so that the motor was adapted for use either with grease or oil. This was on the No. 38-B, which was a modification of the No. 38. Like all compromises which attempt to adopt all the good features of all methods, it was only moderately successful, although it served to keep the motors in service for many years.

Westinghouse No. 49 Motor

This motor had much the same lines as the No. 38-B. It had laminated poles cast in. The fractional pitch or "chorded" type of armature winding was purposely used in this motor to improve commutation, careful shop tests being made with an approximately

full pitch and with various chorded windings to find what would give the best result. It was found that a "throw" of the armature coil, one and one-quarter slots less than full pitch, gave materially better commutation than any other combination. Chorded windings had been used on other types of machinery, to a limited extent, before this, but it is believed that this was the first time that it was used on a railway motor purely for the purpose of improving commutation.

The G. E. No. 800 Motor

This was a new motor gotten out by the General Electric Company to replace the W. P. It was a four-pole machine with two salient and two consequent poles. This was a more symmetrical type of machine than the W. P., but yet was not a purely symmetrical machine, such as the Westinghouse motors from No. 3 on, and the later types of G. E. motors. Its designation of No. 800, was a new method of rating, to indicate its tractive effort instead of its horse-power. Its nominal rating was about 27 h.p. This tractive effort method of rating was carried into several other sizes such as the G. E. 1200 and G. E. 1000.

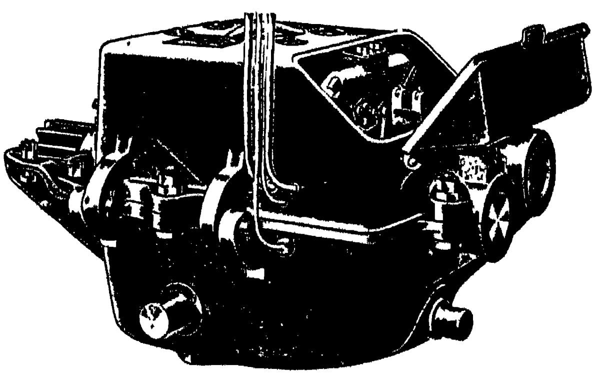


FIG. 13—G. E. 800 MOTOR WITH COMMUTATOR LID OPEN

This G. E. No. 800 motor was a very considerable improvement over the W. P., but possessed certain fundamental defects. For instance, the consequent pole arrangement meant very considerable magnetic fluxes, through the shaft and bearings with consequent tendency for unipolar action in the bearings, the bearing shells and surface forming the collecting brushes. Therefore, there

was a tendency for current in such bearings, as in all consequent-pole machines. It may be assumed that this defect was encountered, for in some of these motors very deep bronze shells were used, apparently for the purpose of introducing so large a gap in the shaft magnetic path that the flux through the bearings would be minimized to a non-injurious point. Moreover as in consequent-pole machines in general, the commutating zones were not truly symmetrical and thus commutation troubles were, to a certain extent, existent.

A similar motor to the No. 800 was the No. 1200. Both of these motors persisted for several years, but were later dropped in favor of the radial pole type with salient poles of which the G. E. 1000 was an example.

From this point on the general design of the direct-current railway motors of all manufacturers has been practically along the same lines. In other words, a definite type has become universal. The fundamental features of this universal type may be classified as follows:—

1—Outside cylindrical or approximately cylindrical yoke.
2—Extension of the yoke to form protecting end housings and to carry the bearings.
3—Radial field poles, usually four in number.
4—Laminated field poles.
5—Bolted-in field poles.
6—Field coils without bobbin shells. (Mummified coils)
7—Drum wound armature.
8—Slotted armature core.
9—Two-circuit or series direct-current winding.
10—Two or more armature coils per slot.
11—Machine wound armature coils, insulated before placing on the core.
12—Relatively thin mica between commutator bars.

It is of interest to note how many of these characteristics appeared in the very early motors. For instance, *1*, *3*, *6*, *7*, *8*, *9*, *11* and *12* all appeared in the original experimental Westinghouse single-reduction motor described, which later was developed into the No. 3. Item No. *2* appeared in the Westinghouse No. 12 and in the Thomson-Houston "W.P." motor. Item *4* first appeared in the Westinghouse No. 38 motor. Item No. *5* appeared in one of the earliest radial-pole G. E. motors and also in the Westinghouse Nos. 56, 68 and 69. Item *10* appeared first in the Westinghouse No. 12 motor.

Thus it is obvious that the Westinghouse No. 3 motor, in its first experimental form (back in 1890), contained nearly all the fundamental features of the present universal type. The end housings carrying the bearings, and the laminated bolted-in poles, constitute the two principal additional developments. Moreover, the experimental No. 3 motor did partially contain the element of enclosing end housings. Thus it may safely be stated that the No. 3 motor practically fixed the type of the modern railway motor.

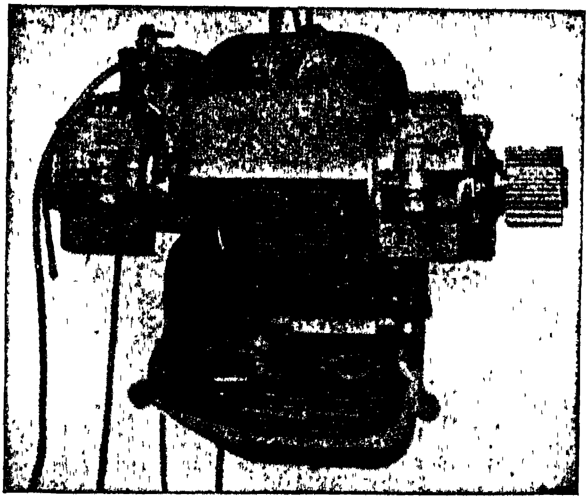


FIG. 14—G. E. 1000 MOTOR, OPEN

It may also be mentioned that there was much argument over the various types of armature windings used by different manufacturers. In connection with the machine-wound coil, as used on the No. 3 motor, many weird claims were made for it In one case within the writer's knowledge, an over-enthusiastic representative of the Company, with practically no knowledge of the matter assured a customer (and he was doubtless sincere in his assurance) that spare coils could be carried along with the car and in case of a burn-out, the trap-door could be lifted and new armature coi's dropped in place. In this case, fortunately, the customer actually knew both what could and could not be done and he had many a good laugh afterwards while telling the incident.

Later Motor Developments

Following the Westinghouse No. 49 and the G. E. No. 1000, the developments of the two companies might be said to be so nearly along the same general lines that the differences were largely in details, although some of the improvements in details were of great importance. A few of the improvements in the Westinghouse later motors might be mentioned. The General Electric Company had already adopted bolted-in-poles, following the Westinghouse No. 38 motor with cast-in poles. The Westinghouse followed in its No. 56 and No. 68 motors with bolted-in poles. Both of these motors had ventilated armature windings and curved field coils, this latter practice being derived from the Walker and Lorain motors, both of which companies had been taken over by the Westinghouse. In the No. 68 motor the alternate

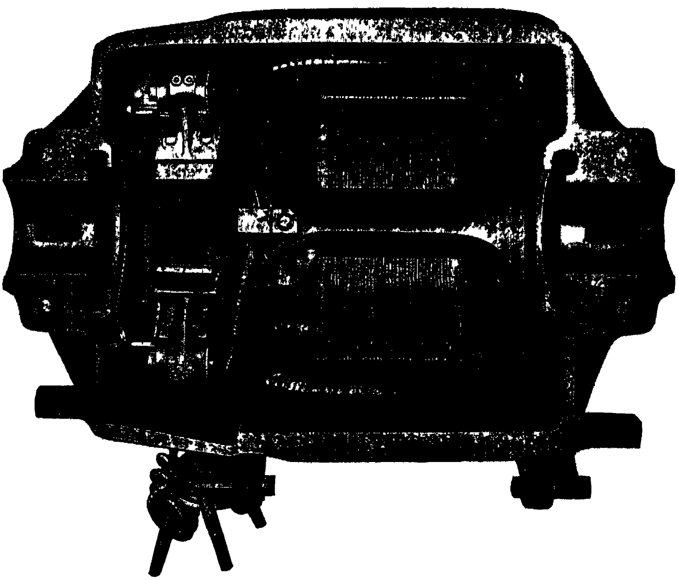


FIG. 15—WESTINGHOUSE NO. 68 MOTOR

corners of the pole tip laminations were cut away, in order to give a higher degree of saturation with heavy load and thus lessen the field distortion and reduce loss in the pole face. This had been common practice for some time in the railway generators. Various detail improvements were also incorporated, notably, brush holders with adjustable spring tension.

The Westinghouse No. 101 Motor

A most important step in the development of the street railway motor came in 1904 in the Westinghouse No. 101 motor. In this motor it was planned to incorporate all the requirements of service as indicated up to that time, together with all the good results found in previous motors. The No. 101-B motor, which was a modification of the original No. 101, has had a most enviable reputation. It contained a number of most desirable features, such as field coils, wound in a straight mould, of copper strap insulated with asbestos paper between turns; a symmetrical armature winding with three co ls side by side per slot and no idle coils, armature coils banded solidly to coil supports, and completely enclosed; armature core and commutator built up on a spider, thus permitting the shaft to be replaced without interfering with the armature winding or core; brushholders insulated in the same way as more modern motors, with micarta tubes protected by cartridge shells, and clamped firmly in position, allowing for radial adjustment.

Probably the most noteworthy improvement in the No. 101 B motor was in the armature bearings and lubrication. The journals were made larger, the shafts of a higher grade of material and the old system of combined oil and grease was discarded and oil-soaked woolen waste was substituted. This motor had the armature bearings carried in housings which were bolted to the top half of the field and clamped between the two halves of the field. The housings had large reservoirs for the oil and waste and allowed for separate gaging of the oil. This motor made a phenomenal record in respect to armature lubrication. Where former motors were overhauled each two or three months, in order to change the bearings, with the No. 101-B it was unnecessary to change bearings until they had been operated several years.

The above improvements were not added without a substantial increase in weight, which, however, was considered well worth while. This motor had a tremendous sale and there are still operating companies who prefer the No. 101-B to any of the more modern motors which have been developed. Other sizes corresponding to the No. 101-B were the No. 92 and No. 93-A.

Commutating Poles in Railway Motors

The next great improvement in railway motors came in 1907 and 1908 in the use of commutating poles. In stationary motor practice, a number of electrical manufacturing companies had used commutating poles for motor work, especially for variable speed service over wide ranges. It was but a direct step from this to the use of commutating poles in railway motors. However, the General Electric Company was the first to put such motors on the market, to be followed soon after by the Westinghouse Company in their No. 300 line of motors, Nos. 305, 306 and 307, being motors which

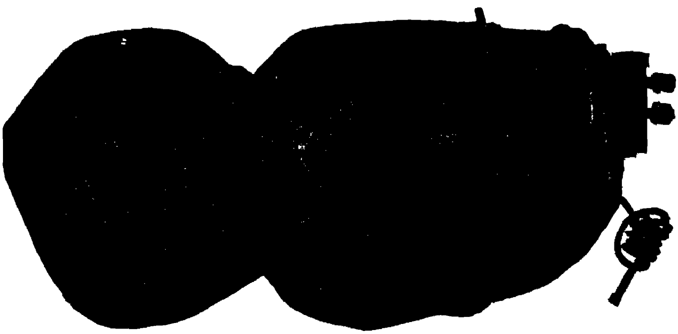


FIG. 16—WESTINGHOUSE NO. 101 B MOTOR

corresponded to non-commutating motors immediately preceding them. These motors had all the mechanical characteristics and general features of design of their predecessors, with the addition of the commutating poles. Since that time commutating poles in railway motors have been so thoroughly established that no new railway motors would be considered without them.

Light Weight Motors

Somewhat later than this an agitation was started against excessive weight in cars, trucks and electrical equipments. This agitation bore fruit, and a weight cutting campaign began which has resulted in the adoption of extremely light weight cars, trucks and motors. The question of car and truck design may not be discussed here, although it looks now as if the weight-cutting campaign has gone past the best limit. However, a large part of the reduction in the weight of motors has been entirely logical and is largely the result of careful design and improvements in ventila-

tion. Motors are now built with large fans, mounted on the pinion end of the armature shaft, which pull air through the armature core and over the surface of the armature and between the field windings, which has made an increase of probably 50 per cent in the continuous rating of the motors. In addition to this, the armature speed has been very considerably increased and the gears have, in many cases, been changed from 3-pitch to 3½, 4 and even 4½.

Open ventilation of the motors has been a natural consequence of the great improvement in insulation made in the last few years. The early motors were made open to the weather but this had to be abandoned because of the large amount of insulation trouble. After a good many years with the enclosed motor, it gradually became the practice to open the motor up somewhat for better ventilation, and finally fans were installed to create a circulation of air, so that now the continuous rating of railway motors is higher per pound than ever before.

TECHNICAL TRAINING FOR ENGINEERS

FOREWORD—This paper was compiled from two addresses, one given by special request before the Pittsburgh Section of the American Institute of Electrical Engineers in 1916, and the other, covering much the same subject matter, was given before the National Association of Corporation Schools at its annual meeting in Pittsburgh, 1916. On account of the favorable comments on the two addresses, they were afterwards combined and printed in the Electric Journal. The author has had a wide experience in the education of so-called "educated" men. Almost since his entrance into the employ of the Westinghouse Electric & Mfg. Company, early in 1888, he has given a considerable part of his time to the development of the more promising young engineers with whom he came in daily contact. Being himself extremely fond of the analytical side of his work, he has been very free in imparting his methods, data and experience to his associates and assistants, thus in fact, although not in name, becoming an educator along advanced lines. He always has been in search of young men of the right turn of mind whom he could develop into "stars" in his profession, and many men prominent in the electrical industry today can speak with pride of the training they received while associated with him. Recognizing that the engineering development work of the manufacturing companies is becoming increasingly difficult from year to year, he has given special attention, during the past several years, to the selection and training of graduates of the technical schools who show, to an unusual degree, certain characteristics and aptitudes which he believes to be necessary in maintaining the high standard of the Westinghouse Company in the engineering field. In other words, he is applying his analytical methods to men very much as he has applied them to apparatus and principles in the past years.—(ED.)

IN the earlier days of the Westinghouse Electric & Mfg. Company many young technical students were taken directly into the various departments and there trained. But in time the student problem became so large and important that an educational department was developed to meet in a systematic manner the growing needs of all departments. This educational department works in conjunction with the other departments in training men and in placing them where they will have opportunities in accordance with their special abilities.

The following remarks represent the writer's own personal opinions based largely upon a comparatively wide experience with the young engineers who have entered the student's course during the past five or six years. In that time this company has taken into

its educational department over one thousand graduates of technical schools from all over the United States and Canada. Of these, several hundred have wished to specialize in engineering, while the aim of the others has been toward the manufacturing and the commer ial lines, both of which require good technical training. The electrical salesman of today is quite technical, regardless of how he got his training. Also the complexities of the electrical business of today require many high-class technical men in the manufacturing departments. As to engineering, it goes without saying that those who follow this branch of the electrical business should be technical men, if they are to advance very far. In consequence the Westinghouse Company takes on technica graduates almost exclusively for its student's course, regardless of what branch of the electrical bu iness they expect to follow.

The writer's personal experience has been very largely with those students who expect to follow the engineering branch of electrical manufa turing. During the past few years he has come in contact with practically all those who leaned toward engineering work. One of the most important considerations in the engineering student problem has been that of fitting the men to the kinds of work for which they are best adapted. In former years this was done in a more or less haphazard manner by trying the men out in different classes of work to see whether they would make good. This procedure proved so unsatisfactory that it became necessary to adopt some method of classifying the students according to their aptitudes and abilities, and then try each one out on that line of work for which he seemed to be best fitted. Obviously, this method was in the right direction, but the primary difficulty lay in determining the characteristics of the individual students. The writer has spent quite a considerable amount of time in the past few years in studying the characteristics of the students to see whether their natural and their acquired abilities can be sufficiently recognized, during the preliminary stages of the work, to allow them to be properly directed toward that field in which they will make the best progress. In this study, in which hundreds of young men were analyzed with regard to their characteristics, many very interesting points developed, quite a number of which have a direct bearing on the subject of technical training. In the first years of this study the results were very discouraging, due largely to the fact that the young men had been brought to us in a wholesale way, regardless of their characteristics or their

suitability for our engineering work. Many of them had no ideas whatever in regard to the kind of work for which they were fitted. Apparently the man who had not, at least partly, made up his mind as to his preferences or his capabilities for some given line of endeavor by the time he had gone through four years of college and then entered our course, had much difficulty in making up his mind after he had been with us a year or two. It developed, in many cases, that he was lacking in decision. This was a very predominant fact in the first few years after the writer had gotten into this work more actively. After a careful study of the situation it was recommended that an attempt be made to get a different class of college men, namely, those who had more definite ideas as to what they wanted and what they were fitted for. This policy was tried, and with great improvement in the grade of men obtained. It is principally from the study of these later men that the writer has been able to draw some of the conclusions which are here given.

One of the most prominent features which has developed from the study of these young men is that in practically all cases the most valuable aptitudes or characteristics which they have shown were possessed by them long before they entered college. In fact, many of them have apparently possessed such aptitudes, more or less developed, from comparatively early childhood. For example, the best constructing or designing engineers all had a strong tendency toward the construction of mechanical toys and apparatus in childhood. In regard to such characteristics, the schools and the colleges have merely directed and developed to a greater extent what is already there. From this viewpoint, therefore, the college simply develops. If the tendency isn't there, it would seem *that there is but little use to try to develop or cultivate it.* Viewed from this standpoint, quite a large percentage of the young men who take up engineering courses in college are quite unfitted for such work. Therefore, one function of the college should be to sort out and classify the young men according to their characteristics, to discourage them from following along any line of endeavor for which they have no real aptitudes, and to direct them into more suitable lines. This applies particularly to technical schools. It might be said that in our present educational system the usual method is to educate the young men and then select the real engineers, this selection being made afterwards through bitter experience. The ideal method, apparently, would be first to select the real engineers and then to educate them. In other words, those who show a

natural aptitude for engineering should be educated along technical lines.

In the technical school one of the first efforts should be toward finding the student's natural aptitudes. Some boys apparently have no leaning toward any special line of endeavor. On the other hand, many boys really have some inherent preference which, however, may not have been strongly enough developed to stand out prominently. Too often his real preference has been entirely neglected or even discouraged. In the writer's own case, as a boy, he was very frequently and severely criticised for his inclination to "waste valuable time" in trying to make what were called "useless things." However, fortunately for himself, no real pressure was brought upon him to prevent him from following his preferences or tendencies, and eventually the "call" was so strong that it took him into the very work which he wanted above all else.

On the other hand, the boy may express a preference for a line of work for which he is entirely unfitted. In other words, this preference may not be based upon natural aptitudes or characteristics and is not a real "call." It is these boys, who are unfitted for the lines which they have chosen, who are a real handicap on their classmates. The class never moves along faster than its average man, and very often at the speed of the poorest men. If these poorest men were eliminated, naturally the progress would be much faster. Apparently the present methods of training have not yet overcome this difficulty, although very many teachers recognize the evil, and are attempting to correct it. This will be referred to again later.

Coming to the technical training of the students, experience indicates that too much specialization is a mistake. He gets enough of that in after years. What is needed is a good, broad training in fundamental principles. In engineering matters, a thorough grasp of such fundamentals is worth more than anything else. By fundamentals is meant basic principles or facts. These should not be confused with theories or explanations of facts. A fact is basic, and does not change, although the theories which explain it may change many times. A thorough knowledge of basic principles will enable a direct answer to be made in many cases, even where the conditions of a problem may appear to be very complex. Take, for example, the perpetual motion fallacy in its various forms. A perpetual motion scheme may be made so complex and involved and may include so many principles and appurtenances that the best

analyst may be more or less puzzled to explain the various relations clearly. But by applying the principle of conservation of energy no further explanation is necessary. This one fundamental fact covers the whole case. In the same way a thorough grasp of some basic principle will often clear up the most complex problems or situations and will allow a conclusive answer to be made. With such a grasp of fundamentals, one is not liable to believe that a "pinch" of some wonderful new powder or chemical, mixed with a gallon of water, will give the equivalent of a gallon of gasoline, and at the cost of few cents. And yet this fallacy "breaks loose" periodically, and is given wide circulation in the news of the day. What is needed in such cases is a little knowledge of fundamental principles.

This very grasp of fundamentals accustoms the boy to think for himself. In other words, it develops his *analytical ability*. As one educator mentioned to the writer some time ago, "If a boy has analytical ability, there is hope for him; if he has none, he is 'punk.'" By analytical ability is not necessarily meant mathematical ability with which some people are inclined to confuse it. By analytical ability is meant the ability to analyze and draw correct conclusions from the data and facts available. This faculty can be cultivated to a considerable extent, although, in the writer's opinion, it originates rather early in life. This is considered by many as the first and foremost characteristic that an engineer must have, and therefore the schools should expend their best energies in this direction.

Allied with a grasp of basic principles is the requirement of a physical conception of such principles as distinguished from the purely mathematical. This can be cultivated, as the writer's personal experience with many students has indicated. As a concrete example of the value of a physical conception the following may be cited:—Three electrical engineers, familiar with induction motor design, are given some new problem regarding the action of an induction motor. One of them immediately thinks of a "circle diagram"; the second thinks of a mathematical formula; the third thinks of flux distributions and conductors cutting them at certain speeds, etc. Assuming equal mathematical skill for these three men, the one with the physical conception of the conductors cutting fluxes has a broader means for attacking the problem than either of the others can be said to have. He can tackle a new condition with better chance of success, as he goes back to the funda-

mental principles of the apparatus. He thus may create, confidently, new formulae and diagrams to meet new conditions and problems.

This physical conception is closely related to the development of imaginative powers, and without such powers highly developed no engineer can expect to advance far in his profession. The man with originality, resourcefulness or with the constructive faculties well developed, or the man who "can see through things" readily, must have strong imaginative powers. This faculty also should be developed to the utmost, but should also be directed. It begins early in some children, but, unfortunately, instead of being directed, it is too often discouraged, both at home and in the school. If the boy in the public school develops a new method of solving a problem, or reaches any conclusion by other than the well-established routine way, he is criticised more often than encouraged for his departure from the beaten track, or rather his instructor's particular methods.

As stated before, the student should be well trained in fundamentals or basic principles. In many branches of engineering this means that he should have a good training in mathematics. Most of the graduates of the technical schools are woefully weak in mathematics. Apparently this is not due entirely to lack of mathematical ability on the part of the students, but largely to defective training in their earlier work. One great defect in many colleges is due to passing the entrants, in algebra and trigonometry, on the basis of their high school training. In most cases this early training in algebra is very defective, as sufficient skill is not developed in the student and the practical side is largely neglected. Algebra and its applications to geometry, trigonometry, etc., should be taught in a more practical manner in the engineering college course, as a foundation for the higher engineering mathematics. The higher the structure is to be, the stronger must be the foundation. If the engineering student is not sufficiently practiced in these elementary mathematics, then he should be drilled specially as a step to further engineering work. In the practical engineering work, beyond the college, skill in the use of algebra and trigonometry is of relatively much more importance than practice in the higher mathematics, for it is needed one hundred times where the other is used once. In the writer's experience with engineers he has reached the conclusion that the principal reason why mathematics are not used more in everyday work is because the average engineers have not

the necessary skill. Most of them claim that they have become "rusty" in such mathematics through disuse. However, in many cases, this excuse is worse than none at all, for the occasion for such mathematics exists in practical engineering work and has been there all along.

In the education of the engineer, higher mathematics forms a very valuable part of the training. One of its uses is to show how one can do without it. In other words, if properly taught, it gives a broader grasp of methods of analysis; it tends to fix certain fundamental principles. However, as a tool in actual engineering work it is seldom required, except in rather special lines. The higher mathematics might be looked upon as a fine laboratory instrument or tool to be used on exceptional occasions, while the ordinary mathematics should be considered as an everyday tool in engineering work, and should be ready at hand at all times.

There has been quite a fad for specialization in engineering training. The writer's personal opinion is that specialization in college training is not advisable, except possibly in a very general way. There has been a false idea in many schools that if a man specialized along some individual line of work it would advance him more rapidly when he leaves school for active work. The writer almost never asks the student in what field he specialized. It is desired to know whether he is a good analyst, if he is fairly skillful at mathematics, if he has the imaginative faculty and what goes with it. Has he initiative, resourcefulness, etc.? Is he a man with a broad grasp of general principles rather than one who has made a special study of one individual subject?

In college training the time spent on commercially practical details is usually largely wasted, as it may give the student entirely wrong ideas. When a young man says that he has had a course in practical design and is positive that he can design, the chances are about ninety-nine out of one hundred that he knows nothing about the really fundamental conditions in practical design. The chances are that he doesn't even know the real starting point in making up a commercial design. Even worse, if he has taken such training seriously, he may have to "unlearn" many of his ideas, if the use of this term is allowable. The mental training and the aid in grasping principles which he may have obtained through his school design is, of course, worth something, but in many cases the same time expended in other channels may produce larger results. Teaching of design should, therefore, be for the

purpose of exemplifying principles rather than practice. There are, of course, some lines of specialization in colleges which lead directly to practical results afterwards. Research work is one of these. However, it is probable that if a large part of the time given to research work by the student in college were expended in acquiring a broader foundation in fundamental principles the results would be better in the end.

As referred to before, there has been one serious defect, in our systems of technical training today, namely, it holds back the leaders and pushes the laggards, thus tending toward mediocrity as the general result. There should be some system in colleges for weeding out the "negatives" in any given line of endeavor. Many of these are simply "misapplications," to use a manufacturing company term. In some other lines they may be highly successful.

In an ideal engineering course each student should be pushed to the utmost of his capabilities. One solution of this problem would be for each teacher to assign a certain amount of work to his students individually, and they should report to him individually on such work, explaining to him fully what they have accomplished. Each man thus could be pushed along independently of his fellows. The weaknesses of the individual men would soon appear. If, for example, it develops that certain of the students are behind in the necessary mathematics, then steps could be taken to correct this defect. Each student would have to think more for himself and would be put more or less upon his own resources. His various characteristics could be studied and developed. He should be made to work out and apply fundamental principles. He would thus practice using his own mind. As soon as it develops that he has no mind of his own, then he could be dropped. In such a course of teaching the advancement of each man would be dependent upon himself, to a large extent. At this point a principle of mechanics can be applied rather aptly. In machines a force does work in overcoming resistance. In man the same principle holds true. No matter how much force a man may have, if no resistance is presented, no result is accomplished. And if the force is small, then the result is also liable to be small. But a smaller force overcoming a larger resistance may result in greater accomplishment than a larger force with but little resistance. An unusually brilliant boy with too small a task set for him may accomplish little. His task must be enlarged to suit his abilities; for, as in machines,

to obtain the greatest result the resistance, or task, must be commensurate with the force acting. Unfortunately, many good men of great capabilities accomplish practically nothing, through too little resistance, due to life being made too easy for them.

Such a course of "forcing," as indicated above, might be difficult to apply in many of the schools as constituted today. But the writer's personal experience indicates that the better class of men will develop rapidly under such treatment, while the laggards are eliminated more quickly. He has tried this system in general on many graduates from the technical schools and unusually satisfactory results have been obtained.

All of the foregoing points to the fact that the mere accumulation of knowledge is not a training, nor an education. The old saying that "knowledge is power" is not technically correct any more than is the statement that torque (or force) is power, to use an engineering comparison. Torque, or force, is not power, but *torque in motion* is power and, to continue this comparison, *knowledge in motion*, or in action, is power. Activity in some form is one of the essential factors.

To sum up, the colleges should aim to develop the student's characteristics, as far as practicable. They should aim to develop analytical ability, imaginative faculty, ability to do independent thinking. They should teach fundamental principles, and the course of teaching should be such as to give the individual student a real grasp of such principles. A broad general training is most desirable for the man who has the ability to do something in the world.

ENGINEERING BY ANALYSIS

FOREWORD—In the latter part of 1916, the engineering students at the Ohio State University decided upon the publication of a college engineering paper, and the author was asked to prepare an article for the first issue. In answer to this request, a paper entitled, "The Electrical Engineer of Today" was submitted. This article appeared in the first issue of the Ohio State Engineer, in January, 1918, and it is here reproduced in practically the same form as the original, except in title.—(ED.)

THE early engineering in any field is usually of the "cut-and-try" kind, followed later by the refinements of more highly trained specialists. A comparatively recent development in industrial and manufacturing engineering is the analytical engineer. By this is meant the engineer who translates facts into relationships, formulae and figures, and eventually retranslates them into other facts. The analytical engineer in this sense does not mean the mere user of figures and formulae. He starts with fundamental principles and laws from which he then draws his conclusions, the applications of which are made directly to the final product without intermediate experimentation. The analytical engineer has led the way to new and more difficult fields of endeavor and many of our most rapid advances have been made under his guidance.

Electrical engineering, is one of the youngest of the engineering lines of endeavor, but its "cut-and-try" period was of comparatively short duration. The coming of the analytical engineer was almost coincident with the rise of electrical engineering as a business. This branch of engineering deals with more or less obscure phenomena, of which there are only indirect evidences in many cases. Many of the laws primarily are only mathematical relationships. Many of them can only be grasped or handled by those who have considerable analytical and mathematical ability. In consequence, even comparatively early in the work, the highly technical engineer was a necessity. Probably in no other branch of engineering, since its first development, has there been as large percentage of men, having high technical training, engaged in the work; and as a consequence, in no other lines of engineering has there been as rapid growth as in the electrical.

Coincidentally with the growth of electrical engineering, there have been rapid advances in the older and better established lines

of engineering, especially in those which have been rather intimately associated with the electrical industry. The steam turbine which now dominates the field of steam prime movers, received its greatest impetus in connection with electrical work, and its present high development may be said to be the product of the analytical engineer. Water-wheel development has also made great advances under much the same conditions.

One characteristic of the analytical engineer of the present time, especially in electrical work, is that he is very often working far ahead of his available data. He is obliged to plot his existing data and experience and then exterpolate for the new points which he finds necessary in his work. He is thus working in the unknown to a greater or less extent, but his ability to analyze and correlate very often leads him to be fairly certain of his results. It is this ability to work with confidence in comparatively unknown fields, which has produced such astonishing results in electrical engineering.

The analytical engineer of today, whether electrical or otherwise, must forsee, through his analysis of data and practice, what the trend of future practice will be. If his analysis shows him that certain lines of development are scientifically more consistent than other lines, he will naturally tend to work along what he considers to be the correct direction. If he sees that certain practices are fundamentally wrong and represent only makeshift conditions, or merely commercial expediency, he will naturally feel that such practices eventually will be replaced. He must weigh both theoretical and practical conditions in determining which direction to work.

With the true analytical engineer there will be no standardization of practice unless such practice has good fundamental reasons back of it. His tendency is rather toward standardization according to certain scientific principles and limitations than by practices which have insufficient basis. The latest standardization rules of the American Institute of Electrical Engineers represent an attempt along this line, and it is a pretty safe prediction that the basic features of these new rules will be retained for many years to come.

Analytical engineering, of a very advanced kind is represented by the modern research and testing departments and laboratories of the big engineering concerns who do electrical and other manufacturing. Much of the technical data, which the designing,

developing and manufacturing departments require, is a direct product of such departments. No progressive industrial establishment of the present time can get along without extensive research departments. Recently Congress has approved of a large Naval Laboratory for research and experimental work, in line with other engineering and industrial organizations.

A good example of modern electrical design work of a highly analytical character, is the present turbo generator. The present huge capacity high speed machines are almost beyond the dreams of ten years ago. These machines are almost entirely the product of the analytical designing engineer. In these machines nearly all previous developments and experience in other lines of apparatus have ounted for little. New methods, new materials, new practices and new limitations have been established in these machines, and for these reasons, the turbo generator engineer has been compelled to work ahead of his data and experience much of the time. For example: the twenty thousand kilowatt, 1800 r.p.m., 60-cycle, turbo generator was undertaken when the ten thousand kilowatt machine of the same speed and frequency was the nearest size from which to obtain data, and this smaller size unit had already been carried up to what were considered as the permissible limits, in many ways. In such case the designer had to overstep his data and limits, and depend largely upon analysis.

Another good example of analytical engineering is the induction motor. While such motors possibly could have been developed by cut and try methods, at great expense and with many failures, yet the present advanced status of this type of apparatus can be considered only as the product of the analyst. The production of cage-wound induction motors with good starting torque, suitable for general purposes, was the result of analysis, not experiment.

In the electrical manufacturing industry the analysts, as represented by the designing engineers, hold an important place. The term is here used broadly to include the designers of systems, applications, methods, etc., as well as apparatus. They form a very necessary part of the organization, especially so in connection with those departments where cut-and-try methods have been largely eliminated. Many of the largest engineering undertakings are on customers' orders, covering apparatus which has never been built before. In most cases, by the time any tests of the completed apparatus are obtainable, the work as a whole

has progressed beyond the point wnere any important changes can be made. Even such preliminary tests as are obtainable in the shop are liable not to tell the whole tale, for the real test or proof of the adequacy of the design comes from duration tests furnished by ctual service. The real troubles may not show up until six months or a year after the apparatus has been put in service. Here is one of the difficulties that the designing engineer encounters; and, the more progressive he is, the more liable he is to run into this very difficulty, simply because he is pushing further into unknown ground. A serious difficulty possibly develops a year or so after the apparatus has been put in service. Then he is criticised both for not having forseen and for not having immediately corrected it. Such criticism might be considered, in one sense, as complimentary, for it is an assumption that he knows much more than he really does. However, most engineers are not particularly pleased over such criticism, for they usually find it hard enough to cure an unknown and unforseen trouble, without being told that they were careless and did not use proper foresight. A true engineer has pride in his work, and a defect or failure, in itself, usually hurts him even more than criticism. He also feels that when a man has done the best he can and has attempted something never accomplished before, he should have sympathy in his trouble, or at least constructive criticism.

It may be added here that in addition to ability to undertake and carry through a given design, it is important that the engineer be able to "let go" of it at the proper time. Each new development or test shows the way to still further improvements or developments, and if each of these is to be incorporated in the design, then it will never reach completion until absolute perfection is attained or the designer has reached the ultimate limit of his ability. Neither of these conditions is practicable in a live manufacturing business, and, therefore, the engineer should be able to let go of his design when a sufficiently good practical result is obtained. Some engineers seem to know just when to stop. This is to some extent dependent upon a proper appreciation of commercial requirements.

To be a successful electrical engineer does not mean one is fitted to be a manufacturing engineer; further, one may be a very good electrical manufacturing engineer and yet not be fitted for electrical design, for this latter is a branch of the industry which re-

quires rather special characteristics. Experience shows that the designing engineer must have a special aptitude for such work regardless of his education or general abilities, if he is to be thoroughly successful. In design work, experience has also shown that combinations of the requisite natural aptitude and the necessary technical training are comparatively rare, and the really successful men in this line of work are but very few in number.

If certain aptitudes and characteristics are essential for the designing engineer it might be asked—what are these essentials? However, it is almost impossible to pick out any characteristic which could be considered as the one essential in the electrical designing engineer, except, possibly, good common sense; but as this is at the bottom of all true success, it should not be considered as peculiarly characteristic of the engineering profession.

As the competent electrical designing engineer must necessarily be an analyst, obviously analytical ability, in the broad sense, must be one of his foremost characteristics. He should also have a certain amount of mathematical ability and training. In general, skill in the ordinary mathematics, such as in algebra and analytical trigonometry is of more use than a mere working knowledge of the higher mathematics. There are certain lines of work in which the higher mathematics are, of course, very valuable and necessary. These, however, represent a relatively small percent of the total field. The young engineer should not become unduly impressed with the idea that ability to use extremely complicated mathematics is the prime requisite. He should, however, recognize that without mathematical aptitude of any sort, he is very greatly handicapped. The "handy man" with mathematics appears to have a decided advantage over others, in practical work.

The engineer who can develop a mental picture or a "physical conception" of what is going on in a machine, in distinction from a purely mathematical conception, appears to have a very considerable advantage over his fellows. The man with both the physical conception and with good mathematical ability will probably go further in analysis than any of the others.

Let us return to one of the conditions which is very necessary in all engineering, namely—a good knowledge of fundamental principles. The engineer should know the derivation of his various methods and formulae. Many of these which are now used by rapid workers are really short cuts or empirical methods which are primarily based upon correct but more complex methods.

Their use, without a proper knowledge of their derivations and, therefore, their limitations, is dangerous and not infrequently leads to serious trouble. Above all the electrical designing engineer should have a broad conception of certain fundamental relationships or laws entirely apart from the mathematics of the case. With a clear understanding of fundamental principles there is much less liability of waste of time and effort from following out impracticable schemes.

There was a time, and not so many years ago, when an electrical engineer could cover almost the entire field. At that time a fairly complete training in the various branches of electrical engineering was possible, but with the widening of the field, it has become too great for the single individual to cover, and the problems have become too difficult for any one man to handle all of them. Therefore, it has become necessary for individual engineers to devote themselves to some special field of endeavor and to leave the broad field to be covered by the co-operation of many specialists. Consequently, the engineering of today is sub-divided into many groups, each more or less distinct in itself, but each overlapping and interrelated with many other groups. The engineer of today is, therefore, always some kind of a specialist, for it is impossible to be otherwise if he is to lead in anything.

It is on account of this specialization that it is so important that the young engineer of today obtain a broad knowledge of the fundamentals of his chosen line of engineering. The same fundamentals underlie the whole electrical field, so that a knowledge of them is about as near as he can come to a broad knowledge of the whole. Such should be obtained as early as possible in his career, for, after specialization begins, his own particular field of endeavor is liable to absorb all of his efforts.

It is now being recognized by the ablest engineers that much specialization in the schools is not an advantage to the student. If the colleges could confine themselves to a broad teaching of fundamental principles they would turn out vastly more effective men than at present. Analytical ability (not necessarily mathematical) is one of the crying needs of the electrical industry of today, as regards its young men. And this need exists in spite of the fact that this industry doubtless gets its full share of the analytical men turned out by the schools. An analytical man *per se* is one who thinks for himself and, therefore, the problem really narrows down to the thinking man. If the schools could turn out

a much higher percentage of thinking men, the engineering profession would be vastly benefited.

There is another quality or characteristic which, while possibly not as valuable as analytical ability, goes a long way toward success, namely—persistency. A brilliant mind with but little persistency back of it, will usually accomplish less than a much less brilliant mind backed by great persistency. This latter characteristic has turned many an apparent failure into positive success. A brilliant man without persistency is liable to pass from scheme to scheme and perfect none of them. However, persistency alone usually accomplishes no more than brilliancy alone. Men have expended years of patient effort along lines which a little common sense analysis would quickly have shown to be impracticable. Here is persistency gone to waste.

The emphasis placed upon the above mentioned characteristics is not intended to belittle other very important ones, such as initiative, originality, resourcefulness, etc. These qualities might be classed even higher than analytical ability and persistency by some persons, and possibly rightly in some lines of effort. But in the higher electrical work the conditions may be otherwise. Here one may have strong initiative, but be utterly unable to make any great progress due to lack of analytical ability; he may have great originality, but, lacking the fundamentals, be unable to touch on the higher work; he may be exceedingly resourceful, but be limited only to lesser things due to lack of knowledge of basic principles, and, thus, inability to handle advanced work. However, a leader must have all of these qualities to a certain extent. Now and then a man is found who has all of them to a fairly high degree, combined with unusual analytical ability and perseverance. Such a man eventually is liable to become known as a genius, but it should be remembered that genius is of two kinds,—creative, in the sense of being able to think in new fields, and constructive, in the sense of being able to use present known facts and principles to bring about successful results.

Then there is another feature which may be referred to, namely, the commercial side of engineering. An electrical manufacturing business lives by the goods, not the engineering, which it sells. The successful designer of such goods must, therefore, have considerable knowledge of commercial conditions or he cannot design adequate or competitive apparatus. This is a feature of the business about which the young engineer, fresh from school, knows

nothing. This appears to be a very difficult thing for some engineers to acquire, while certain of them never really do so. On the other hand, it has been said of some very good engineers that they ought to have been salesmen, because they grasped so readily the customer's conditions and requirements. The broad gauge electrical designer is usually quite successful in aiding the salesman, because he sees the commercial bearing of his engineering work.

This relation of the engineer to the commercial side of the business brings up another point, namely, his ability to talk clearly and logically in private and in public. It was once supposed that an engineer never had to talk in public and that all he had to do was to go off in a corner, by himself, and use a slide-rule. But that day is long past, for now the man who knows most about the apparatus must be able to tell others what he knows. Presumably in all large concerns there are men who are seldom or never sent outside on account of their inability to make a good presentation of a subject. Assuming equal ability otherwise such men are of less value than those who can make a good presentation of any given matter. In general, a good logical thinker can develop into a fairly good logical speaker through practice.

The foregoing has had most to do with electrical designing engineers, but while they are a very important part of the industry, yet they are not the only engineers in the electrical manufacturing business. In fact, the electrical industry today is managed almost entirely by men who should be classed as engineers. A large percentage of the electrical salesmen of today have had a very good engineering training of one kind or another. In fact, in many lines they must have such training in order to be successful. In the manufacturing part of the business, many of the leading men are also good engineers. Also many of the high executives in the industry are trained engineers of high grade.

In conclusion it may be said that this is an age of engineering construction. It is, or rather it forshadows, the golden age of the engineer. His successes and attainments have led him to view hopefully hitherto totally unattainable things, and in consequence his problems are becoming increasingly difficult. At no time has such boldness been shown in attacking the problems of nature for the benefit of mankind, and it is the engineer in one guise or another who is behind the attack, and his aim almost invariably is something which is ultimately for the advancement of humanity. Construction, not destruction, is his preference,

He is an optimist and not a pessimist. In research work he is delving into the unknown in search for properties, principles and laws of nature and of material. He is making vast strides in the conservation of natural resources, by the economical generation and utilization of power. In transportation he is bringing the whole world together. He is making steel and concrete the rule in constructions, doing away with more perishable materials.

Engineering should be considered of highest rank among the professions. No engineer need apologize for his calling. He should feel the greatest pride in it, for it may be said that it is the very heart and soul of material progress.